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Water Mist Fire Tests For Class II & III Engine Rooms

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16. Abstract

Twenty-three fire tests were conducted to determine the ability of typical current water mist technologies to extinguish fires specified in the International Maritime Organization (IMO) fire test procedure for Class II and Class III engine rooms. Sixteen of the twenty-three tests used fire scenarios specified in the IMO test procedure. They were conducted using nozzles installed at a 5 m height and 1.5 m spacing in a large test facility (2800 m^2 area and 18 m height) in which no additional enclosure surrounded the nozzles. Two types of mist heads were tested: a low pressure nozzle operating between 1.2 MPa and 1.5 MPa with flow per head between 12.0 and 13.4 ℓpm and a high pressure mist head consisting of seven-nozzles operating at 6.9 MPa flowing 5.3 ℓpm per head. The fire tests selected from the IMO procedure included 6 MW diesel spray fires on top of the IMO engine mockup, a shielded 6 MW diesel spray fire adjacent to the mock-up, a 1 MW shielded diesel spray fire adjacent to the mock-up, and a wood crib within a 2 m^2 pan filled with heptane. The results of this test program indicate that current water mist technology, as represented by the two systems used in the test program, is unlikely to be capable of extinguishing test fires in the IMO fire test protocol for Class III engine rooms. In tests with thirty-six or one hundred low pressure nozzles, fires were not significantly affected by the water mist. Similarly, when thirty-six or ninety high pressure mist heads were installed, extinguishment also did not occur.

To further investigate mist system capabilities, a ceiling was then placed over the nozzles covering an area of 188 m^2. Using ninety high pressure nozzles, the test fires were not extinguished. A 940 m^3 enclosure was then formed by dropping tarpaulins to the floor from the ceiling. A 4 m^2 vent was placed in the wall. With the ninety high pressure nozzles, the 6 MW spray fire on top of the mock-up was extinguished. When the 6 MW fire was shielded beside the mock-up, the fire was not extinguished. With the vent closed, the 6 MW shielded spray fire was extinguished. Under the same test conditions, a 1 MW shielded diesel spray fire and a 0.1 m^2 heptane pool fire were not extinguished.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

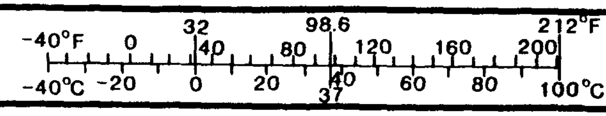
*1 in = 2.54 (exactly).

PRESSURE

psi	pounds force per square inch	6894	Pascals	Pa

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PRESSURE

Pa	pascal	1.45 (10^{-4})	pounds force per square inch	psi

PREFACE

We acknowledge the support of the United States Coast Guard Research and Development Center, Groton, Connecticut, under Delivery Order DTCG39-95-F-E00280. In particular, we are grateful for the technical advice and participation of Mr. Richard L. Hansen, Contracting Officer's Technical Representative for this project. We also gratefully acknowledge the support of Professor Robert G. Zalosh through the Center for Firesafety Studies, Worcester Polytechnic Institute. The fabrication plans for the IMO engine mock-up were developed by Mr. William R. Brown of Factory Mutual Research Corporation (FMRC). Fire testing at the FMRC Test Center could not have been successfully completed without the skills and dedication of the FMRC Test Center staff.

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Executive Summary

Large-scale fire tests were conducted to determine the capability of current water mist technology to meet the requirements of the interim International Maritime Organization (IMO) test method[1] established at the 39th meeting of the Fire Protection Subcommittee (FP39). The test method is for equivalent water-based extinguishment systems in Class II (500 m^3 < and > 3000 m^3) and Class III (> 3000 m^3) machinery spaces. The test method was established to evaluate mist systems in large machinery spaces where the effects of boundaries and small volumes would not play a role in extinguishment performance.

Eight (8) especially challenging test scenarios derived from the thirteen IMO test scenarios, were used for evaluation against a low pressure high flow nozzle (operating between 1.2 to 1.5 MPa and 11.9 to 13.4 lpm) and a high pressure low flow nozzle (6.9 MPa and 5.1 lpm). Low pressure nozzles were tested with either a thirty-six (36) or one hundred (100) nozzle grid. High-pressure nozzles were tested with either a thirty-six (36) or ninety (90) nozzle grid. These grids covered areas of 83 m^2 and 232 m^2. The testing was conducted with nozzles installed at a 5-m height and 1.5 m spacing in a large test facility (2800 m^2 area with 18 m height).

The results indicate that the current water mist technology, as represented by the two systems used, is not likely to extinguish all the test fires in the IMO fire test protocol for Class III engine rooms. In tests with either thirty-six or one hundred low pressure nozzles, fires were not significantly affected by the water mist. Similarly, when thirty-six or ninety high pressure nozzles were installed, extinguishment also did not occur.

To further investigate mist system capabilities, a ceiling was placed over a portion of the test area (188 m^2). Using the ninety high pressure nozzles, the fires were not extinguished. A 940 m^3 enclosure was then formed by dropping tarpaulins to the floor from the ceiling. A 4 m^2 vent opening was placed in the enclosure. A 6 MW spray fire was extinguished; however, when the spray fire was shielded under a 1 m obstruction, the fire was not extinguished. With the vent closed, the 6 MW shielded spray fire was extinguished. Under the same conditions a 1 MW spray and 0.1 m^2 heptane pan fire were not extinguished.

These results indicate that an enclosure and specifically its size are important parameters in the extinguishment of fires using water mist. This led to further investigations into the role of oxygen depletion as a mechanism of extinguishment for water mist. Those investigations will be reported in a future report.

I

BACKGROUND

The objective of the tests described below was to determine the capability of current water mist technology to meet the requirements of the interim International Maritime Organization (IMO) test method[1] established at the 39th meeting of the Fire Protection Subcommittee of IMO (FP39). The test method is for equivalent water-based fire extinguishment systems in Class II and III machinery spaces of category A and cargo pump-rooms. At FP39 (London, June 27 - July 1, 1994) a fire test procedure was developed for equivalent water-based fire extinguishment systems for machinery spaces and cargo pump-rooms on ships regulated under Safety of Life at Sea (SOLAS). The procedures were primarily based upon a test protocol submitted by the Swedish delegation at FP38[2]. Although the fire test procedures are, in principle, appropriate for any water-based extinguishment system, the fire-test-procedure working group at FP39 focused on water mist systems. Only limited data[3] were available to the working group on water mist systems as applied to flammable liquid fires in engine rooms. A schematic of the engine mock-up (adapted from Reference 1) used in the fire test protocol and in the current study is shown in Figure 1.[1] A description of the prescribed fire tests developed at FP39 is given in Table 1 with fuel sources described in Table 2.

The working group initially felt that, given the limited testing experience, a protocol was appropriate for spaces 10 m x 10 m x 5 m (high). For Class I engine rooms (500 m^3 in volume), fire testing would be conducted using the engine mock-up (Figure 1) in a 500 m^3 room with a 5 m ceiling height and natural ventilation through a 2 m x 2 m door opening. For spaces greater than 500 m^3, and in particular ceiling heights greater than 5 m, no data were available to the working group at FP39. (Note that Class II engine rooms are between 500 m^3 and 3000 m^3 in volume, while Class III engine rooms are in excess of 3000 m^3.) The use of the IMO engine mock-up for spaces with ceilings greater than 5 m was considered at FP39 to be particularly problematic because the mock-up cannot simulate the complexity of obstructions, and surface areas likely to be present in higher

[1]Note that the mock-up as shown in Reference 1 has a solid steel plate which is 3.5 m long, rather than 3 m as shown in Figure 1. The shorter plate facilitated fabrication of the mock-up.

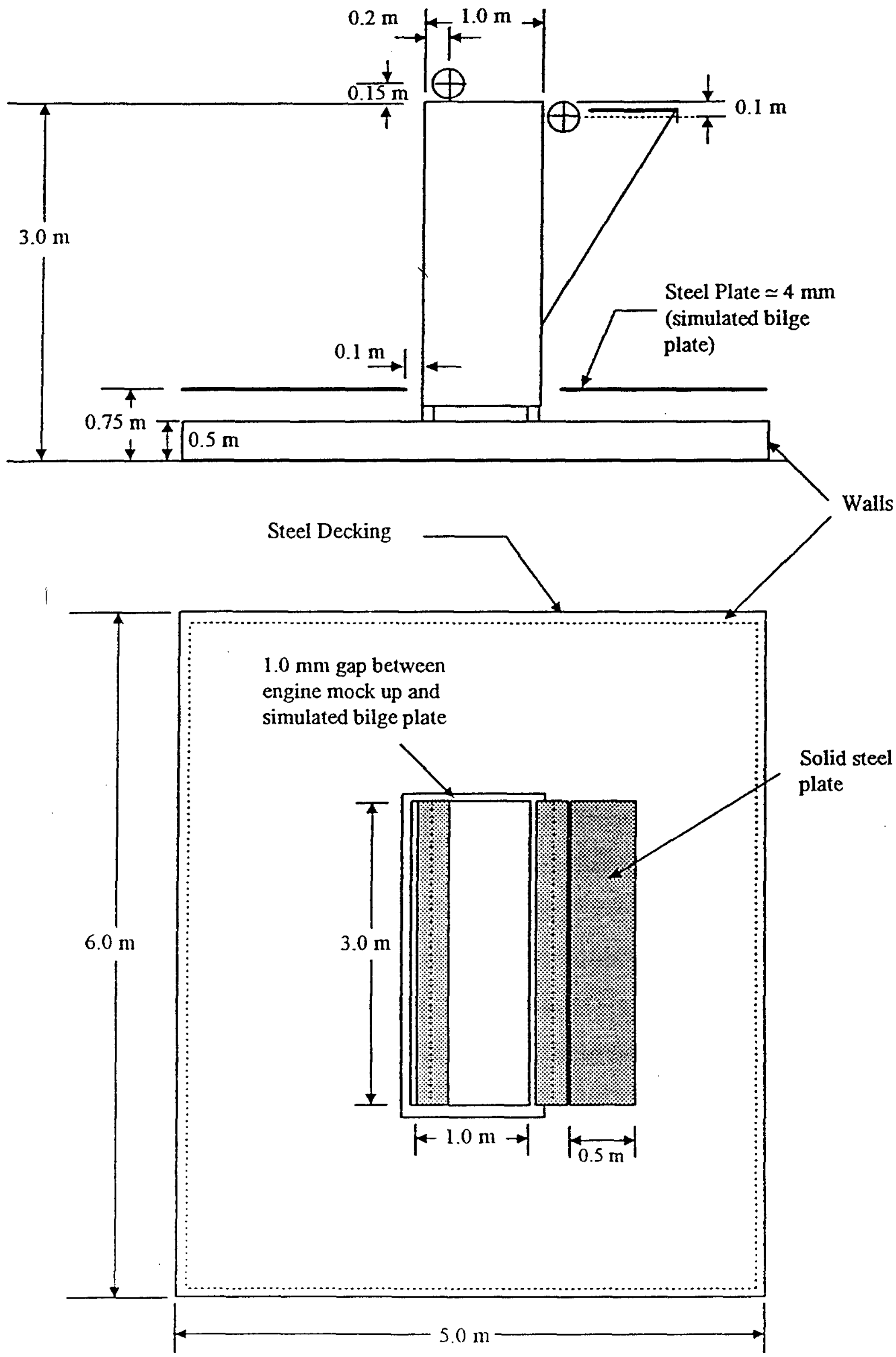


Figure 1. IMO Engine Mock-Up (West Side and Plan View)

TABLE 1

INTERIM IMO ENGINE ROOM FIRE TESTS[†]

Test No.	Fire Scenario	Test Fuel
1	Low pressure horizontal spray on top of simulated engine between agent nozzles	Commercial fuel oil or light diesel oil
2	Low pressure spray on top of simulated engine centered with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 meter away	Commercial fuel oil or light diesel oil
3	Low pressure concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m from the end of engine	Commercial fuel oil or light diesel oil
4	Combination of worst spray fire from Tests 1-3 and fires in trays under (4 m^2) and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
5	High pressure horizontal spray fire on top of the simulated engine	Commercial fuel oil or light diesel oil
6	Low pressure low flow concealed horizontal spray fire on the side of simulated engine with oil spray nozzle positioned 0.1 m from the end of engine and 0.2 m^2 tray positioned 1.4 m from the engine end at the inside of floor plate	Commercial fuel oil or light diesel oil
7	0.5 m^2 central under mock-up	Heptane
8	0.5 m^2 central under mock-up	SAE 10W30 mineral based lubrication oil
9	0.5 m^2 on top of bilge plate centered under exhaust plate	Heptane
10	Flowing fire 0.25 kg/s from top of mock-up.	Heptane
11	Class A fires wood crib (see Note) in 2 m^2 pool fire with 30 s preburn.	Heptane
12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure, low flow spray nozzle positioned horizontally 0.5 m from the front edge of the plate. When the plate reaches 350°C, the system is activated. Following system shut-off, no reignition of the spray is permitted.	Heptane
13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

[†]The wood crib is to weigh 5.4 to 5.9 kg, and is to be dimensioned approximately 305 x 305 x 305 mm. The crib is to consist of eight alternate layers of four trade size 38.1 x 38.1 mm kiln-dried spruce or fir lumber 305 mm long. The alternate layers of the lumber are to be placed at right angles to the adjacent layers. The individual wood members in each layer are to be evenly spaced along the length of the previous layer of wood members and stapled. After the wood crib is assembled, it is to be conditioned at a temperature of 49 + 5°C for not less than 16 hrs. Following the conditioning, the moisture content of the crib is to be measured with a probe type moisture meter. The moisture content of the crib should not exceed 5% prior to the fire test.

TABLE 2

OIL SPRAY FIRE TEST PARAMETERS

FOR USE WITH TABLE 1

Category A Engine-Room Class 1-3

Fire type	Low pressure	Low pressure, Low flow	High pressure
Spray nozzle	Wide spray angle (120 to 125°) full cone type	Wide spray angle (80°) full cone type	Standard angle (at 6 Bar) full cone type
Nominal oil pressure	8 Bar	8.5 Bar	150 Bar
Oil flow 333333	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ± 0.002 kg/s
Oil temperature	20 ± 5°C	20 ± 5°C	20 ± 5°C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

spaces, on which mist impingement can occur. For a ceiling height of 5 m, the scale of the engine mock-up and the shielding are reasonable. Furthermore, recent testing[4] has shown that the mock-up is also adequate for simulating engine rooms with a ceiling height of 7.0 m. For Class II and III engine rooms with much higher ceilings, the working group was thus faced with the need to develop a method of simulating larger volumes and an installation protocol that could be used with the engine mock-up to extend the usefulness of the test results to larger volumes.

Increased compartment volumes and ceiling heights reduce the effectiveness of mist by increasing the availability of oxygen, reducing the effectiveness of steam production and by increasing the difficulty of delivering a sufficient concentration of mist to the hazard location. The working group approached the problem of increased volume by mandating that the mockup tests be conducted within a test hall at least 300 m^2 in area and with a ceiling at least 10 m in height. FP39 established that one level of nozzles in the fire test are to be installed no more than 5 m above the test floor over the mock-up engine with no ceiling installed directly above the nozzles (no enclosure walls are constructed within the 300 m^2 area). For engine rooms with ceiling heights greater than 5 m, nozzles passing the mock-up fire tests are to be installed at vertical intervals of 5 m (or less, depending upon the elevation of nozzles above the floor used in the fire tests) and the same horizontal spacing as in the mock-up tests. Based upon test results[4], at FP40 the maximum vertical distance was increased to 7.5 m.

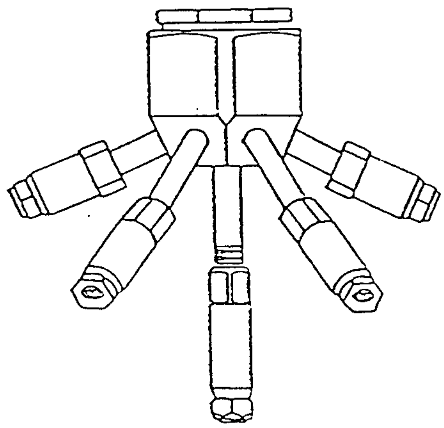
Extinguishment of the mock-up fires with no enclosure walls or ceiling would conservatively simulate nozzle installation in a larger compartment because nozzle performance would not depend upon nozzles installed at higher elevations. All nozzles in the engine compartment are to operate when the mist system is activated[1]. The nozzle installation method described above is thought to be quite conservative because at the highest elevation in the compartment, it duplicates the spray densities and concentrations used in the mock-up fire tests while increasing densities and concentrations are generated at lower elevations. With a lack of data on full scale engine room testing in volumes larger than 500 m^3, the working group felt this conservative approach was necessary. No data were available at FP39 to evaluate if mist technology can adequately suppress fires such as those in the mock-up tests under conditions in which nozzles are not installed directly under a ceiling. Evaluation of the test protocol for compartments greater than 500 m^3 was therefore the key objective of the current program.

The capabilities of existing commercial mist systems have been extensively assessed in testing sponsored by the U.S. Army(5) in spaces less than 1000 m^3. In particular, the U.S. Army, in its Water Mist Machinery Program(5), has identified levels of performance of existing water mist technology that can be expected in IMO fire tests (Table 1) in a 745 m^3 space under a 4.5 m ceiling. A variety of nozzles were investigated at 1.5 m spacing. One of them was a prototype developed for the U.S. Army Water Mist Machinery Space Program(5), a seven-nozzle, high pressure prototype (Figure 2) consisting of Spraying System nozzles, six LN2 and one central LN8 nozzles manifolded together. The seven-nozzle head was operated at a nominal pressure of 6.9 MPa and 5.1 lpm. This mist head was used in IMO tests in enclosures with areas of 83 m^2, 109 m^2 and 166 m^2, and a ceiling height of 4.5 m. Only an area of 83 m^2 was protected. The larger areas of 109 m^2 and 166 m^2 were formed by moving one wall further away and enclosing the larger volume. The fire test results from the IMO tests were generally adequate (extinguishment in less than fifteen minutes) and form the primary baseline for interpreting the results in the proposed tests. The results seemed to indicate that successful testing in a space with a 100 m^2 area and a 5 m ceiling, as required at FP39 for Class I engine rooms, would assure adequate protection for spaces of larger areas with a 5 m ceiling. The results of the current study, as discussed below, put this conclusion in doubt. Furthermore, the inability of the water mist technology (identified in the U.S. Army Water Mist Machinery Space Program) to perform adequately in the IMO fire tests in the current study, makes it appear unlikely that water mist protection can be extended to volumes greater than 500 m^3 and ceiling heights greater than 5 m following the current IMO protection philosophy.

II

TECHNICAL APPROACH

The ability of existing water mist technology to perform adequately in the IMO fire test protocol was evaluated in the current program in a series of twenty-three fire tests. All fire tests were conducted within a large test area of approximately 2800 m^2 with a ceiling height of 18 m. In one



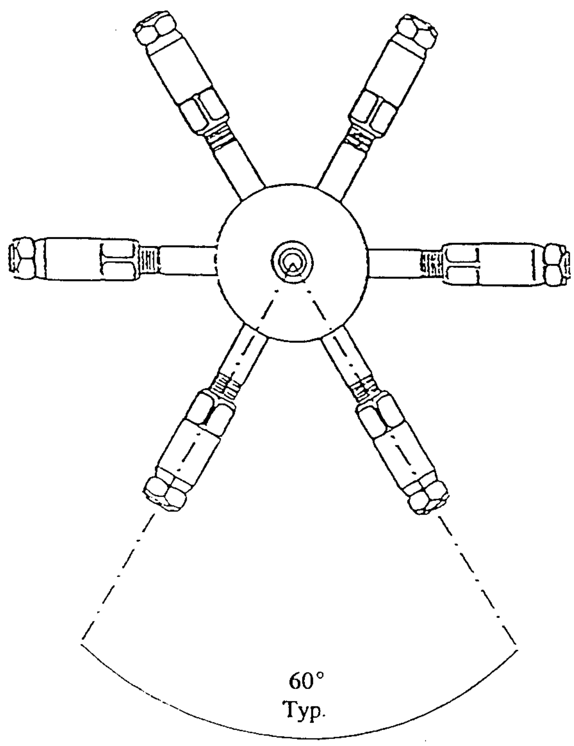


Figure 2. Spraying Systems seven-nozzle head

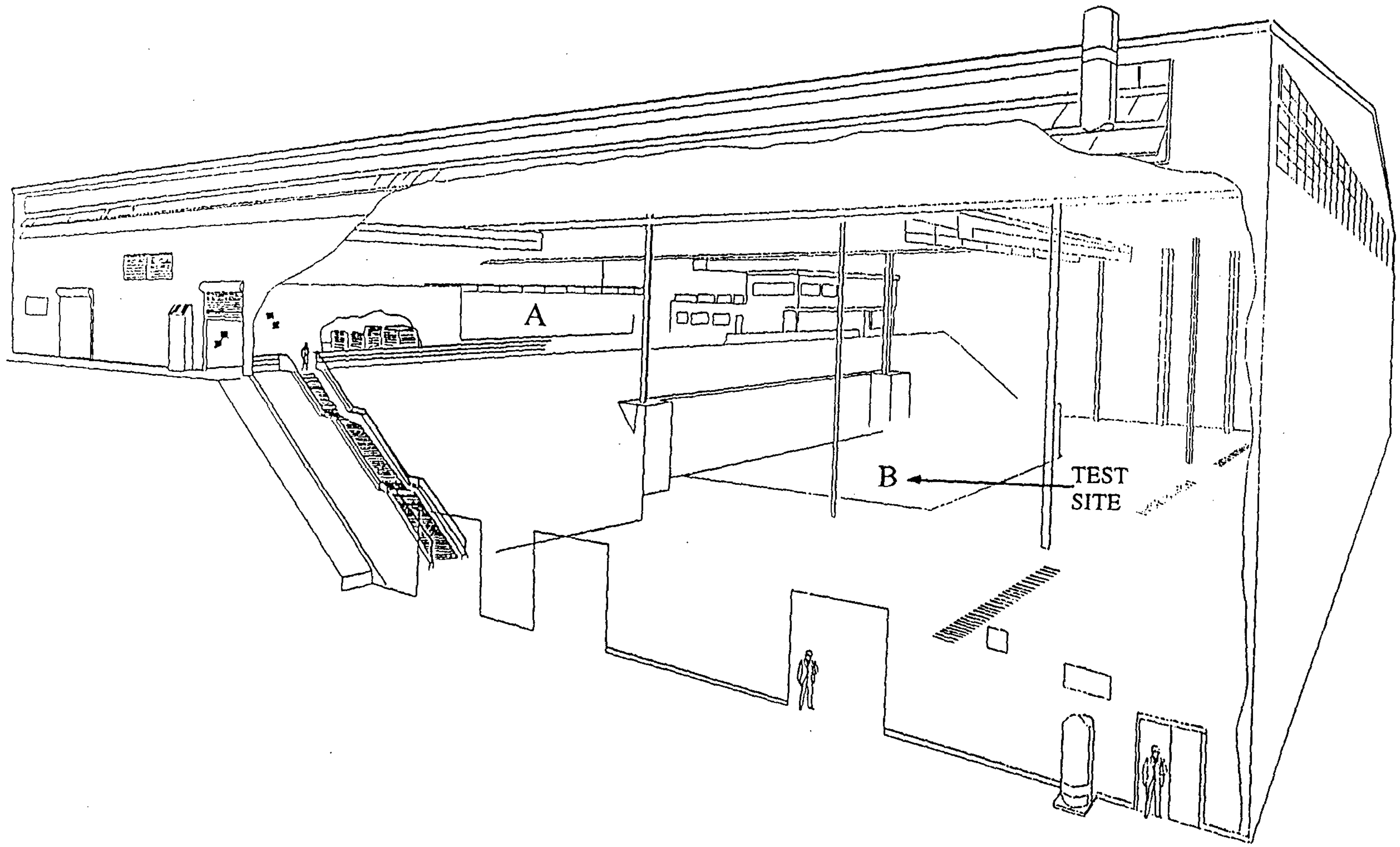
series of tests, using either low pressure or high pressure, single-fluid nozzles, protection was limited to an area of 83 m^2 (with nozzles at 5 m above the floor). As discussed below, because the water mist nozzles did not perform adequately, i.e., no fires were extinguished in these fire tests, protection was extended to an area of 232 m^2 for the low pressure nozzles and 209 m^2 for the high pressure nozzles. In these tests, the fires were again not extinguished. Therefore, in a final series of tests, the IMO fire test procedures were modified by the addition of a ceiling at 5 m in some tests (with no walls) and by the creation of a 940 m^3 enclosure (5 m ceiling) in other tests. In some of these tests, fires were extinguished, providing further information on the capabilities and limitations of current water mist technology. Note that in the original test plan reported in Reference 6, the use of a ceiling was not envisioned, and more fire scenarios from the IMO test scenarios were to be investigated. The many fire tests in which extinguishment did not occur dictated a change in the test plan after consultation with the program monitor.

III

TEST FACILITY AND WATER MIST SYSTEMS

IMO fire tests were conducted at the FMRC Test Center at W. Glocester, RI. A pictorial sketch of the test building is shown in Figure 3 and a floor plan in Figure 4. Overall dimensions are 61 m x 76 m with two floor-to-ceiling heights, 9.14 m and 18.29 m. Tests were conducted at the "60 ft site" (18 m high ceiling) in an area approximately 18 m x 18m. Scaffolding (platform supports) was erected surrounding the 18 m x 18 m space as shown in Figure 4. Bar joists were installed above the scaffolding to support the water supply branchlines and main feedline as shown in Figure 5a.

The branchlines were 1 in. stainless steel tubing and the main feedline was 4 in. schedule 80 steel pipe. With a maximum flow of 1325 lpm (350 gpm) through the 4 in. line, the pressure loss was negligible. The main feed line was installed below the branchlines in order that it would be fully charged prior to the discharge of the mist nozzles. With ten branchlines, the maximum flow through any pipe was 66 lpm (17.5 gpm); friction loss in the 1 in. branchlines was also negligible. Compression fittings were used throughout with connections to the branchlines from the main



A: Test Area - 9.14 m high section

B: Test Area - 18.29 m high section

Figure 3. Factory Mutual Test Center (Pictorial)

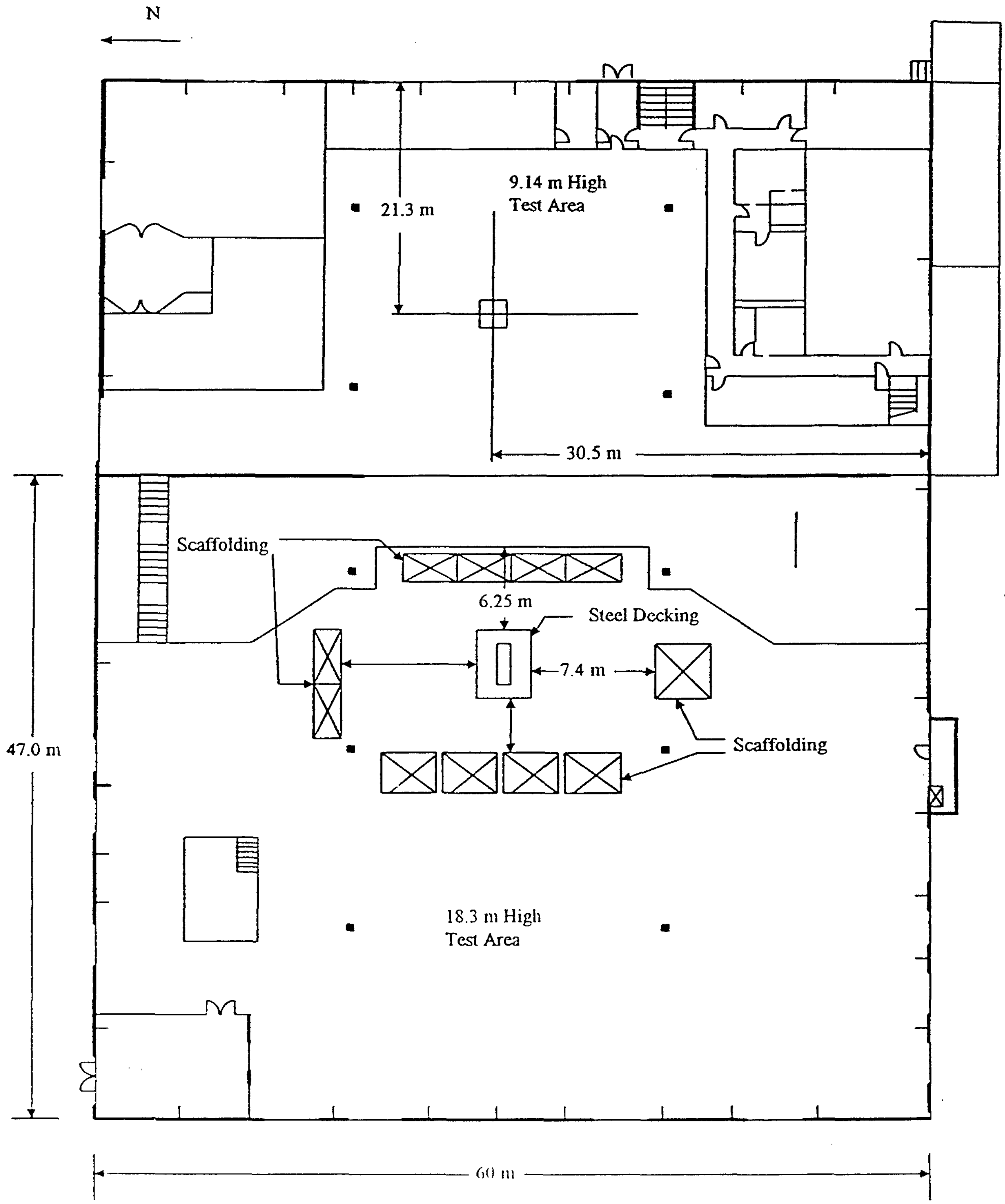


Figure 4. Floor Plan of Factory Mutual Test Center

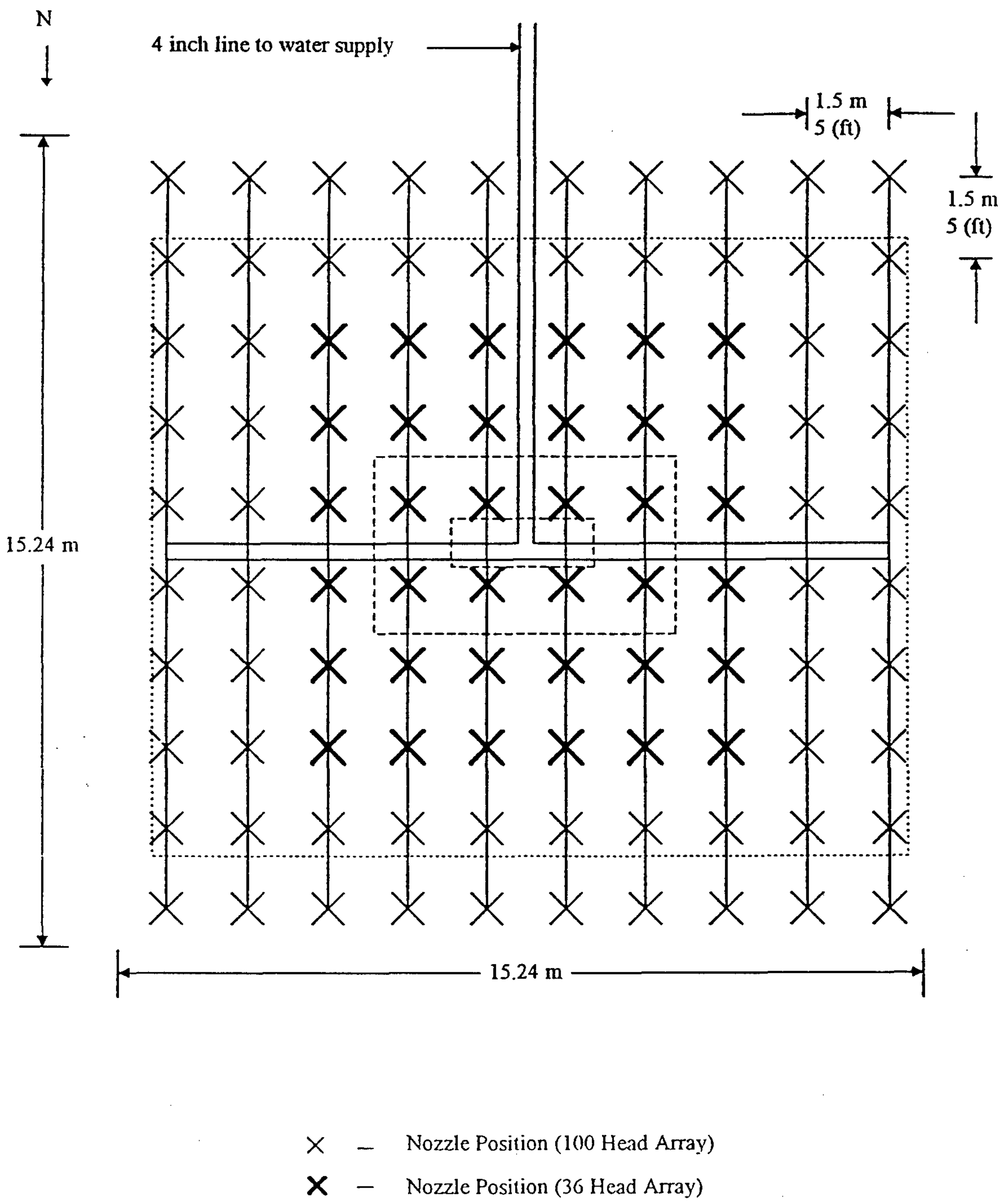


Figure 5a. Mist Nozzle Layout

feedline via threadolets. In one series of tests, 36 low-pressure nozzles or 36 high-pressure mist heads were installed in the central 83 m^2 area with the other outlets plugged (see Figure 5a). In the next series of tests with enlarged protection areas, low pressure nozzles were installed at 100 locations covering a 232 m^2 area. In subsequent tests with enlarged protection areas, the high pressure mist heads were installed at 90 locations covering an area of 209 m^2. Because these tests were unsuccessful, in the following tests using the high pressure mist heads, first a ceiling was created by installing corrugated sheet metal above the branchlines covering an area of 188 m^2. Following these tests, the ceiling was surrounded by a tarpaulin hanging down to the floor. The enclosure and mist head positions are shown in Figure 5b. In some tests a 4 m^2 vent was introduced in the north wall of the enclosure as in the IMO fire tests for 500 m^3 engine spaces. In others the vent was eliminated. It is important to note that the enclosure created by the sheet metal ceiling and tarpaulin walls was not tight and there was considerable leakage at the edges where the tarpaulin met the ceiling or formed a corner. Gaps in the ceiling were as large as 5 cm in some locations .

As noted above, two types of nozzles were investigated at 1.5 m spacing. One of them was the prototype developed for the U.S. Army Water Mist Machinery Space Program[5], the seven-nozzle high pressure prototype (Figure 2) consisting of six Spraying Systems LN2 and one LN8 nozzles manifolded together. The seven-nozzle head was operated at a nominal pressure of 6.9 MPa and 5.1 lpm. The flow at that pressure was determined for an individual seven-nozzle head using a calibrated turbine meter. The flow from the center LN8 nozzle operating alone was 2.3 lpm and the flow from a single LN2 nozzle was 0.64 lpm. Thirty of the seven-nozzle heads were available from the U.S. Army Water Mist Machinery Space Program for use in this test program. Due to unavailability of the LN2 and LN8 nozzles, substitutes were used to make up the full complement of 36 or 90 mist heads. The substitute recommended by the manufacturer consisted of six Spraying Systems TX2 and one TX8 nozzle manifolded together in the same way as the original prototype. At a nominal operating pressure of 6.9 MPa, the flow rate was 5.4 lpm, also determined for an individual seven-nozzle head using a calibrated turbine meter. The flow from the center TX8 nozzle alone was 2.4 lpm at that pressure, while the flow from a TX2 nozzle was 0.53 lpm. Data from the nozzle manufacturer[7,8] indicate the volume median drop sizes were approximately the same for the U.S. Army prototype and the substitute nozzle at 6.9 MPa. The LN2 and TX2 have volume median

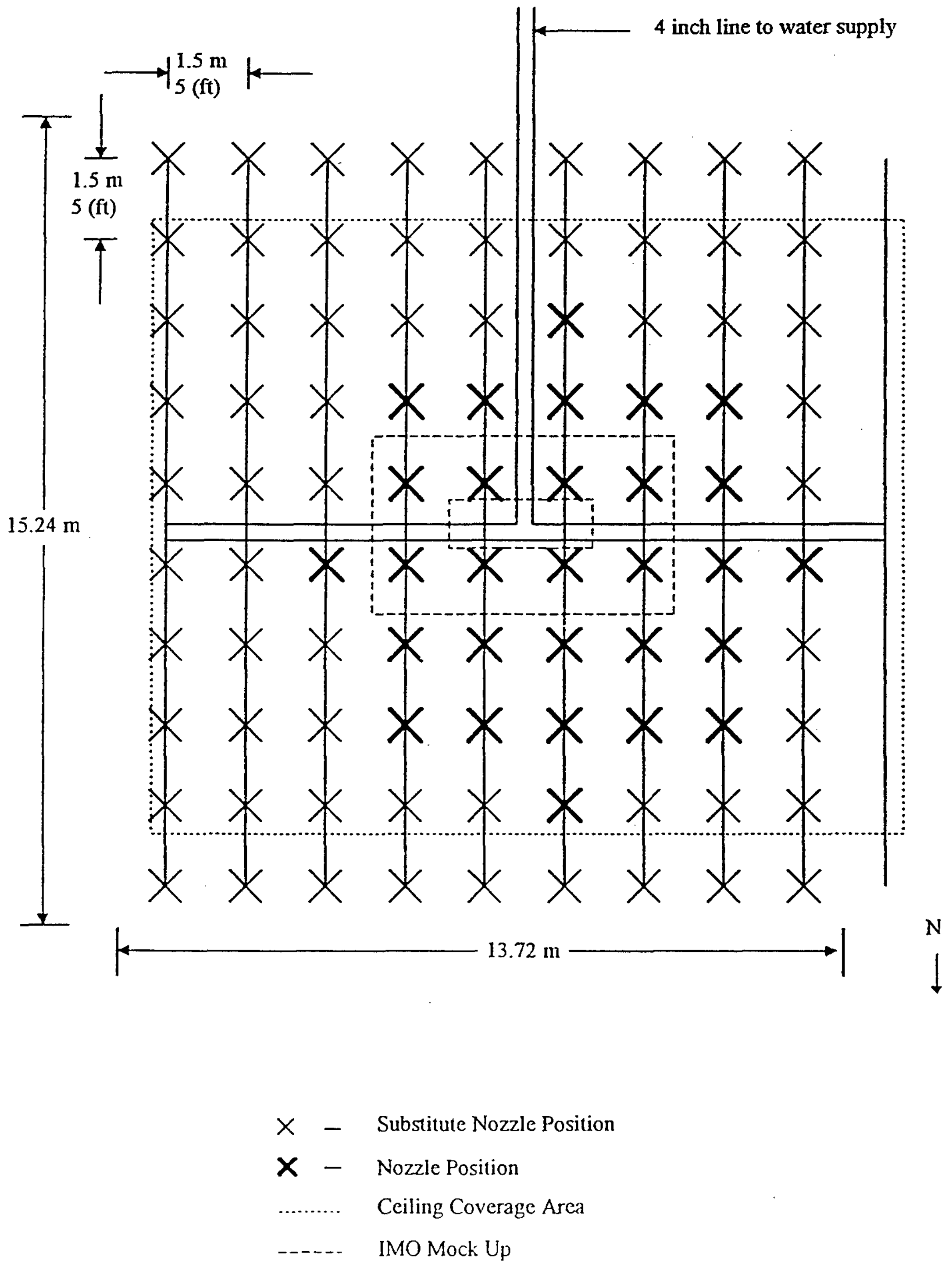


Figure 5b. Mist Nozzle Layout Showing Ceiling and Wall Locations

drop diameters of 95[7] and 90[8] microns, respectively. The LN8 and TX8 each have volume median drop diameters of 95[7,8] microns. Figure 5b shows the locations of the substitute nozzle.

The other water mist nozzle selected for the program was the Grinnell AM-10 (Figure 6) operating between 1.2 and 1.5 MPa and 11.9 and 13.4 lpm. The volume median drop diameter at 1.2 MPa is 300 microns[9]. The K-factor for this nozzle was determined to be 3.46 lpm/ $(\text{bar})^{1/2}$. This nozzle was also investigated using the IMO fire test procedure in the U.S. Army Water Mist Machinery Space Program[5] in the same enclosure as the prototype. The Grinnell AM-10 was only tested, however, within an enclosure with an area of 83 m^2. The results were also generally adequate, with extinguishment occurring in less than 15 min. (Note that the Spraying Systems seven-nozzle mist head and the Grinnell AM-10 have both also been tested as part of the study to be reported in Reference 4.)

The water supply for the Spraying Systems nozzles (6.9 MPa) consisted of four positive placement pumps (NLB Corporation). Three of the pumps had a rated capacity of 151 lpm at 14 MPa, with the remaining pump having a rated capacity of 76 lpm at 14 MPa. The pumps were connected by high pressure hose to a 4 in. (101 mm) schedule 80 manifold connecting to the main feedline. The NLB pumps are diesel driven. The water supply for the Grinnell nozzles (1.4 MPa) was supplied by the FMRC Test Center supply with a maximum capacity of 2200 lpm at 1.6 MPa.

Two different nozzles were used for the fuel spray fires. The nozzles employed in the current program were the same as those used in IMO testing by the Swedish National Testing and Research Institute (SP). These are Lechler nozzle number 460.728 (low pressure spray 0.16 kg/s at 8 bar, see Table 2) and Lechler 460.406 (low pressure, low flow spray, 0.03 kg/s at 8.5 bar). The low pressure, low flow diesel fuel was supplied from a low pressure fuel pump. The nozzle pressure was monitored using a pressure gauge.

The engine mock-up was fabricated from 2 mm thick sheet steel by an outside vendor using the design developed by FMRC from the IMO specifications and shown in Figure 1.

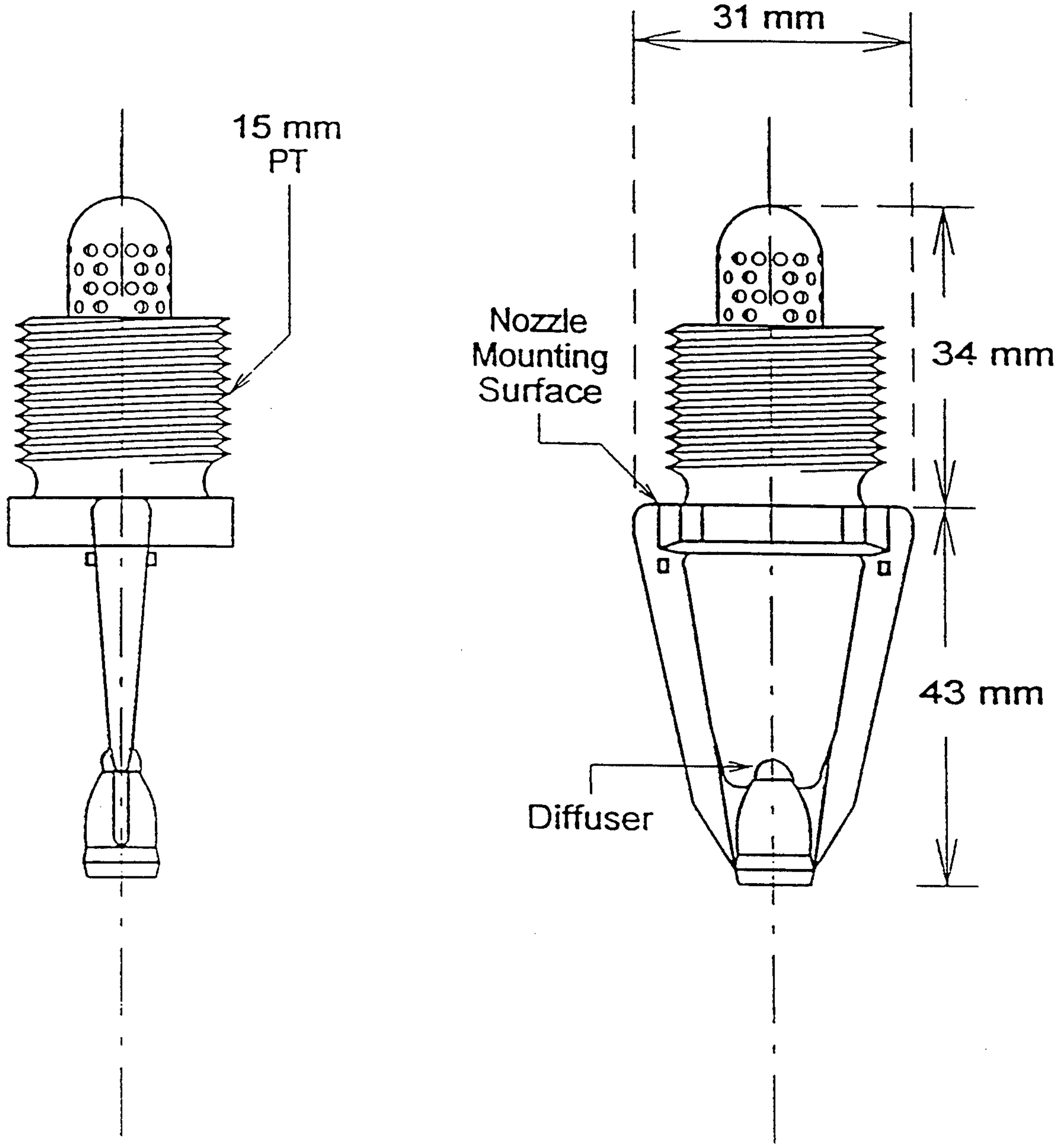


Figure 6. Grinnell AM10 Mist Nozzle

IV

INSTRUMENTATION AND DATA ANALYSIS

Instrumentation consisted of gas sampling to measure oxygen, carbon monoxide, and carbon dioxide concentrations at the base of the fire. Sampling lines were relocated as needed from test to test. Infrared gas analyzers (Beckman 864) were used to measure carbon monoxide and carbon dioxide. A paramagnetic analyzer (Beckman 755) was used to measure oxygen concentration. Gases were filtered and dried prior to entering the analyzers. The analyzers were calibrated at the beginning of a test day using zero and span gases.

Gas temperatures were measured using 28 gauge, type K thermocouples. Thermocouples were used to measure flame temperatures (upon which extinguishment times were based) and temperatures of entrained air. In addition, two thermocouple trees were installed adjacent to the mock-up to a height of 5 m. Each tree consisted of five thermocouples spaced at 1 m vertical distances. The instrument locations are described in Section V in connection with the description of tests.

The water supply manifold pressures were monitored through recording of pressure transducers in the 4 in. main feed line.

Data from thermocouple channels, gas analysis channels, pressure transducer, and event channels (ignition, water discharge, etc.) were recorded using a Hewlett Packard HP 1000 data acquisition system. Data were acquired at a rate of 1 scan per second. The data were converted to engineering units using calibration curves (also using the HP 1000). A listing of the primary equipment used in this program is given in Table 3.

V

DESCRIPTION OF TESTS AND PROCEDURES

A subset of the IMO fire tests were conducted for each nozzle configuration. Tables 4 through 6 list the test configurations and extinguishment times for the program. Tables 4 and 5 correspond to tests using no ceiling and no walls as in the IMO Class II and Class III engine room tests

TABLE 3

WATER MIST FIRE SUPPRESSION TESTING
FMRC TEST EQUIPMENT

Instrument	Manufacturer	Model No.	Serial No.	Range
Pressure Transducer	Eaton Corp.	PT100DG2CA	130672	0-500 psig @ 0-5 VDC
"	"	PT100GG2CAB	130673	0-2500 psig @ 0-5 VDC
Power Supply	Hewlett Packard	E3610A		0-8 VDC @ 3A
Pump	Nat'l Liquid Blasting Corp.	6150	198011-1	6000 psi max
"	"	"	3818	"
"	"	1012-D	28025	"
"	"	6125D	977121	"
Fuel Supply Pump (Diesel)	Hayes Pump	FH32	I-10263-0120	
Fuel Supply (Motor)	US Elec Motors	F012B		3 gpm
Pressure Gauge	Foxborough Co.			0-200 psi
Fuel Supply Pressure Vessel (Diesel)	Scott & Fetzer Co.		136264	
Pressure Gauge	USG			0-160 psi
IR Analyzer (CO Measurement)	Beckman	864	103430	0-5000 ppm
IR Analyzer (CO_2 Measurement)	"	"	105644	0-10%
O_2 Analyzer (CO Measurement)	"	755		0-25%
Pump (Gas Analysis	Dayton Electric Co.	2Z866	0790	
Flow Meters	Dwyer Instrument Co.			
Video Camera	Sony	CCD-FX710	1015994	

TABLE 4

SUMMARY OF CLASS II & III ENGINE ROOM
IMO FIRE TESTS
LOW PRESSURE SYSTEMS

Test No.	Test Config.	Nozzle/ pressure (MPa)	Nozzle No.	Fire Scenario	Test Fuel	Exting. Time	Instrument Layout	Test Duration (min)
1	No ceiling/ no walls	Grinnell 1.2	36	1 MW shielded spray fire	Diesel	None	A	10*
2	"	"	"	6 MW shielded spray fire	"	None	A	15
3	"	Grinnell 1.5	"	"	"	None	A	15
4	"	"	"	6 MW spray fire	"	None	B	1**
5	"	"	"	"	"	None	B	11
6	"	Grinnell 1.5	"	Wood Crib 2 m^2 pan	Pine/ Heptane	None	C	17
7	"	"	100	6 MW shielded spray fire	"	None	A	15
8	"	"	"	6 MW spray fire	"	None	B	15
9	"	"	"	Wood Crib 2 m^2 pan		None	C	17

*Test aborted to avoid damage to test facility.

**Test aborted due to a piping failure.

TABLE 5

SUMMARY OF CLASS II & III ENGINE ROOM
IMO FIRE TESTS
HIGH PRESSURE SYSTEMS

Test No.	Test Config.	Nozzle/ pressure (MPa)	Nozzle No.	Fire Scenario	Test Fuel	Exting. Time	Instrument Layout	Test Duration (min)
10	No ceiling/ no walls	Spraying Systems (7.1)	36	6 MW shielded spray fire	Diesel	None	A	15
11	"	"	"	6 MW spray fire	"	None	B	7*
12	"	"	90	1 MW shielded spray fire	"	None	A	15
13	"	Spraying Systems (6.9)	"	"	"	None	A	15
14	"	"	"	6 MW shielded spray fire	"	None	A	15
15	"	"	"	6 MW spray fire	"	None	B	9*
16	"	"	"	Wood Crib 2 m^2 pan	Pine/ Heptane	None	C	19

*Test aborted to avoid damage to test facility.

TABLE 6

SUMMARY OF CLASS II & III ENGINE ROOM
MODIFIED IMO FIRE TESTS
HIGH PRESSURE SYSTEMS

Test No.	Test Config.	Nozzle/ pressure (MPa)	Nozzle No.	Fire Scenario	Test Fuel	Exting. Time	Instrument Layout	Test Duration (min)
17	Ceiling/ no walls	Spraying Systems (6.9)	90	Wood Crib in 2 m^2 pan/ 0.1 m^2 pan	Pine/ Heptane/ Heptane	None	D	20
18	"	"	"	6 MW spray fire	Diesel	None	B	15
19	Ceiling/ walls/ 4 m^2 vent	"	"	"	"	3.5 min. 0_2 ~ 18%	B	6
20	"	"	"	6 MW shielded spray fire	"	None	A	15
21	Ceiling/ walls/ no vent	"	"	6 MW shielded spray fire & 0.1 m^2 pan	Diesel/ Heptane	Spray: 5 min pan: 2.75 min 0_2 ~ 16.5%	E	6.5
22	"	"	"	0.1 m^2 pan	Heptane	None	E	22
23	"	"	"	1 MW shielded spray fire & 0.1 m^2 pan	"	None	E	15

prescribed in FP39[1]. Table 6 corresponds to modified tests in which a ceiling or a ceiling and walls were installed to determine the capabilities and limitations of current water mist technology.

Four basic test conditions were investigated in the program: IMO Tests 1, 3, 6 and 11; see Table 1. Other IMO test conditions would have been investigated had the test results been more promising. The four IMO fire tests which were investigated had previously been successfully extinguished in less than 15 min. using the Spraying Systems prototype in a 745 m^3 enclosure[5]. None of the tests in the current program involved fires in the bilge (see Table 1, IMO Tests 7, 8 and 13), which have been shown in the U.S. Army Water Mist Program to be quite challenging[5].

All fires were specified and located to meet the IMO test requirements. The following correspondence can be made between the fire scenario description in Tables 4 through 6 and Table 1 (supported by Table 2). IMO Test 1 is the same as the 6 MW spray fire, IMO Test 3 is the same as the 6 MW shielded spray fire, IMO Test 6 is the same as the 1 MW shielded fire, and IMO Test 11 is the same as the crib fire in the 2 m^2 pan of heptane. Note that in some tests listed in Table 6 a 0.1 m^2 heptane fire was used on the simulated bilge plates.

Tables 4 through 6 also list the instrumentation layout associated with each fire test. Figures 7 and 8 show two views of layout A corresponding to the 1 MW or the 6 MW shielded spray fires. The only difference between the two test conditions was the nozzle used to produce the spray fires.

Figures 9 and 10 show two views of layout B corresponding to the 6 MW fire on top of the engine mock-up. Figures 11 and 12 show two views of layout C corresponding to the crib/heptane pool fire test. Figures 13 and 14 show layouts E and F which are, respectively, modifications to the crib/heptane pool fire (layout C) and the shielded spray fire (layout A).

At the beginning of each test day, water flows from the pumps were initiated to check water supply pressures. The main 4 in. (10 cm) feedline, installed below the nozzle branchlines, was thus charged for the fire tests. Gas analyzers were calibrated at the beginning of the day using zero and span gases.

Fuel flows for spray fires were monitored by pressure and fires were ignited when required fuel pressures were established. Prior to ignition, background data were acquired for one minute and video recordings were initiated. A pre-burn time of 15 s was used prior to initiating water flow to the nozzles for the low pressure water mist nozzles in tests with spray fires. Thirty-second pre-burn

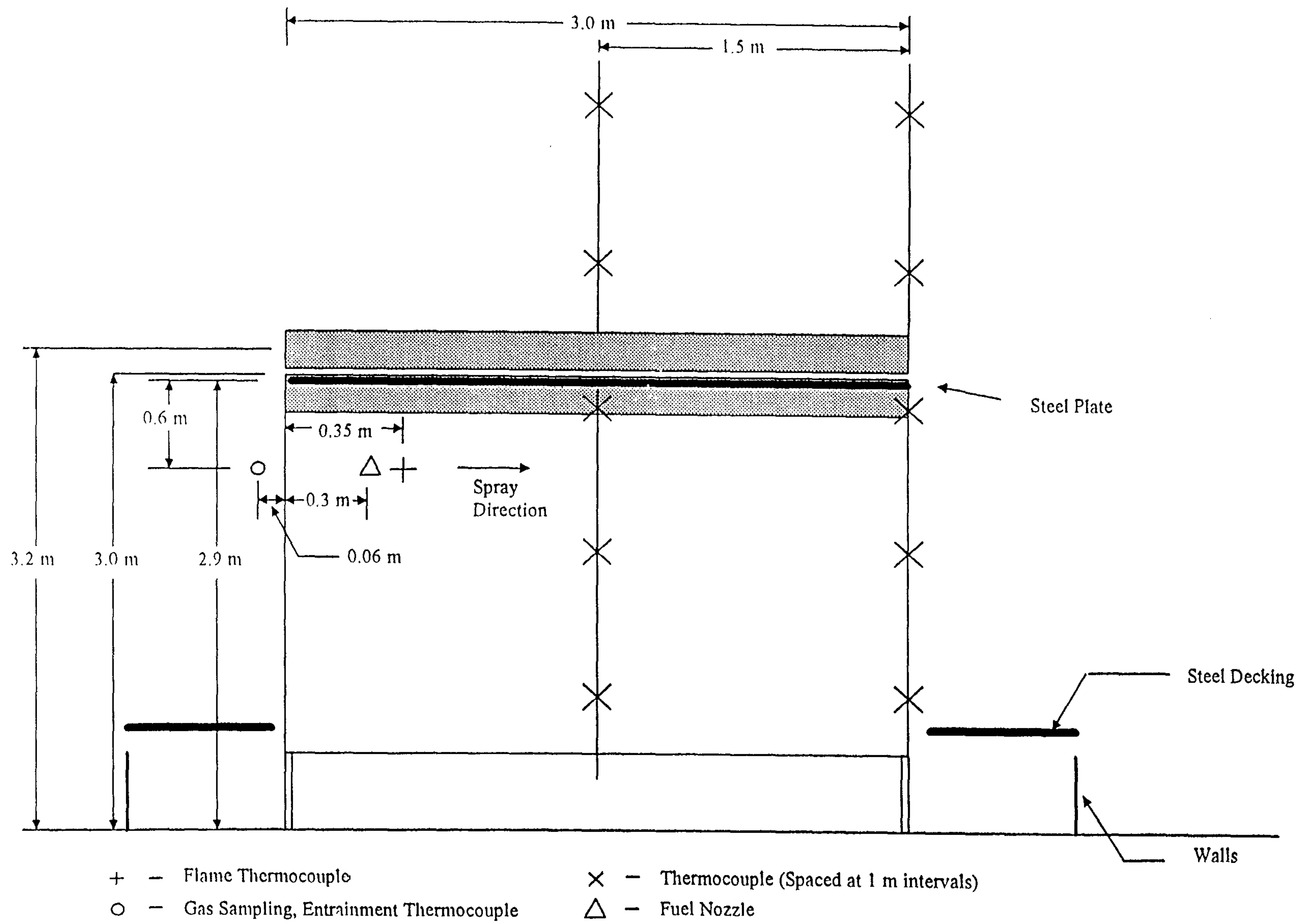
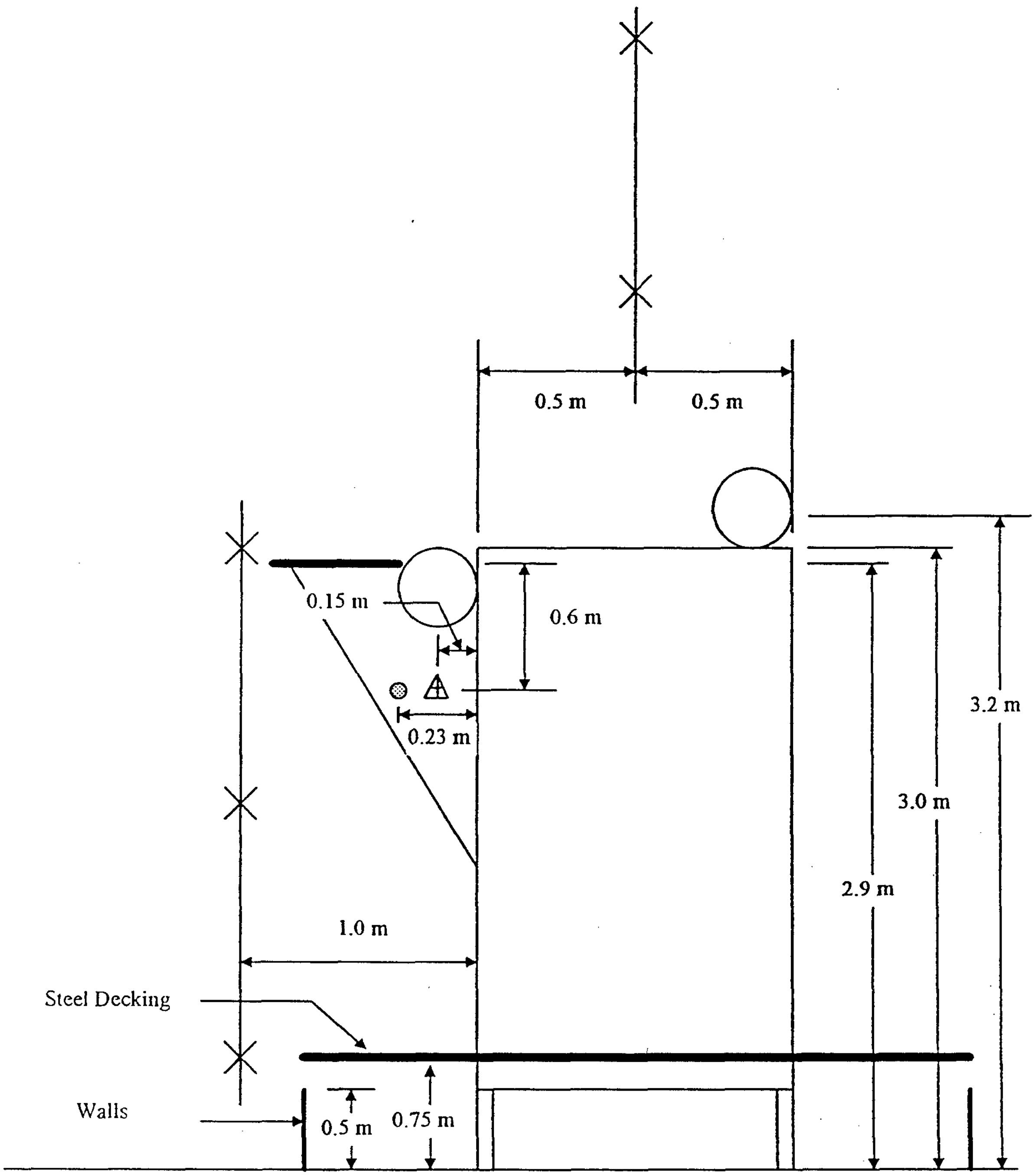


Figure 7. Test Instrumentation Layout A - North Side



× — Thermocouple (spaced at 1 m intervals)

Flame Thermocouple, Fuel Nozzle

Gas Sampling, Entrainment Thermocouple

Figure 8. Instrumentation Layout A - West Side

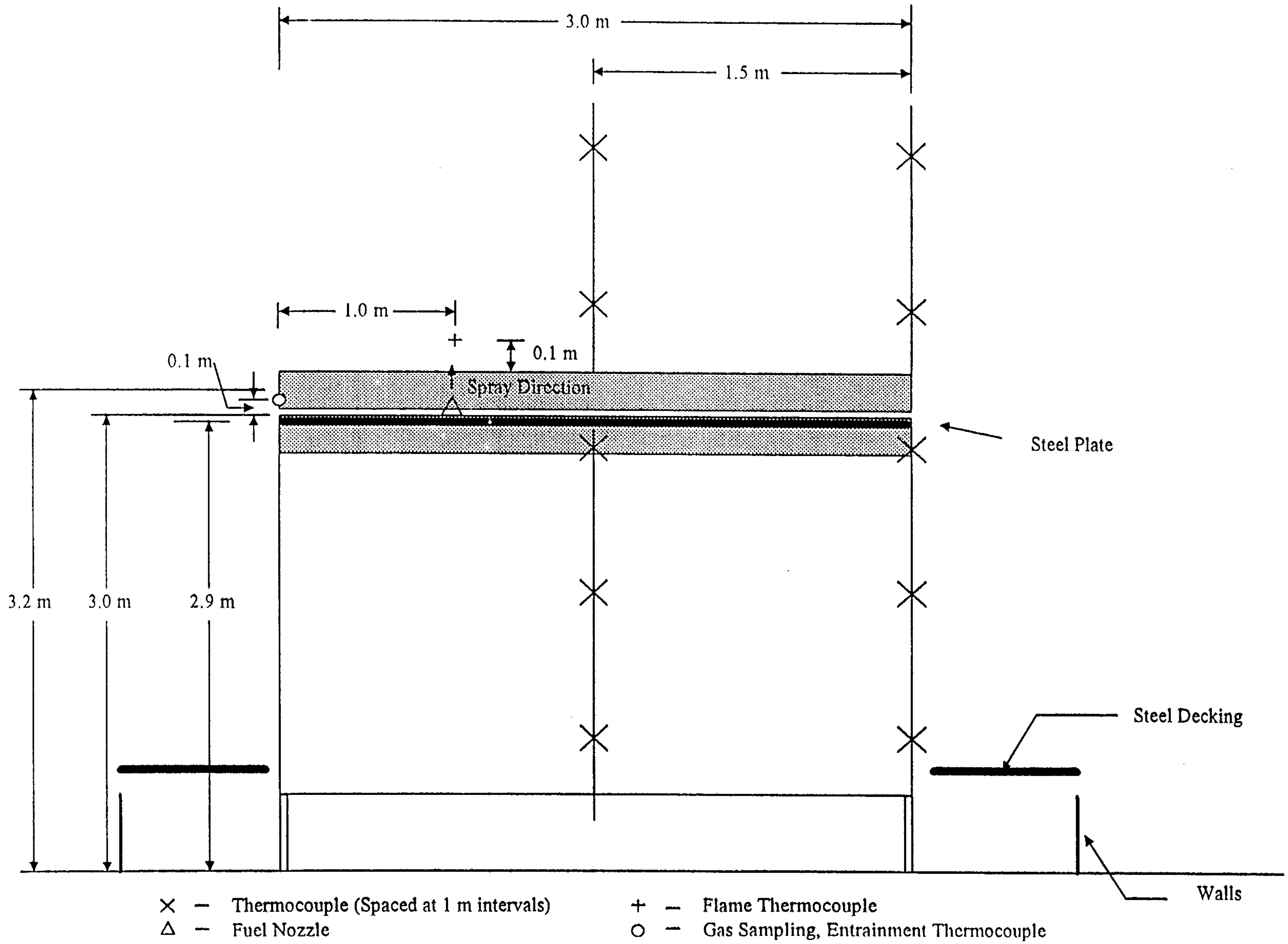


Figure 9. Instrumentation Layout B - North Side

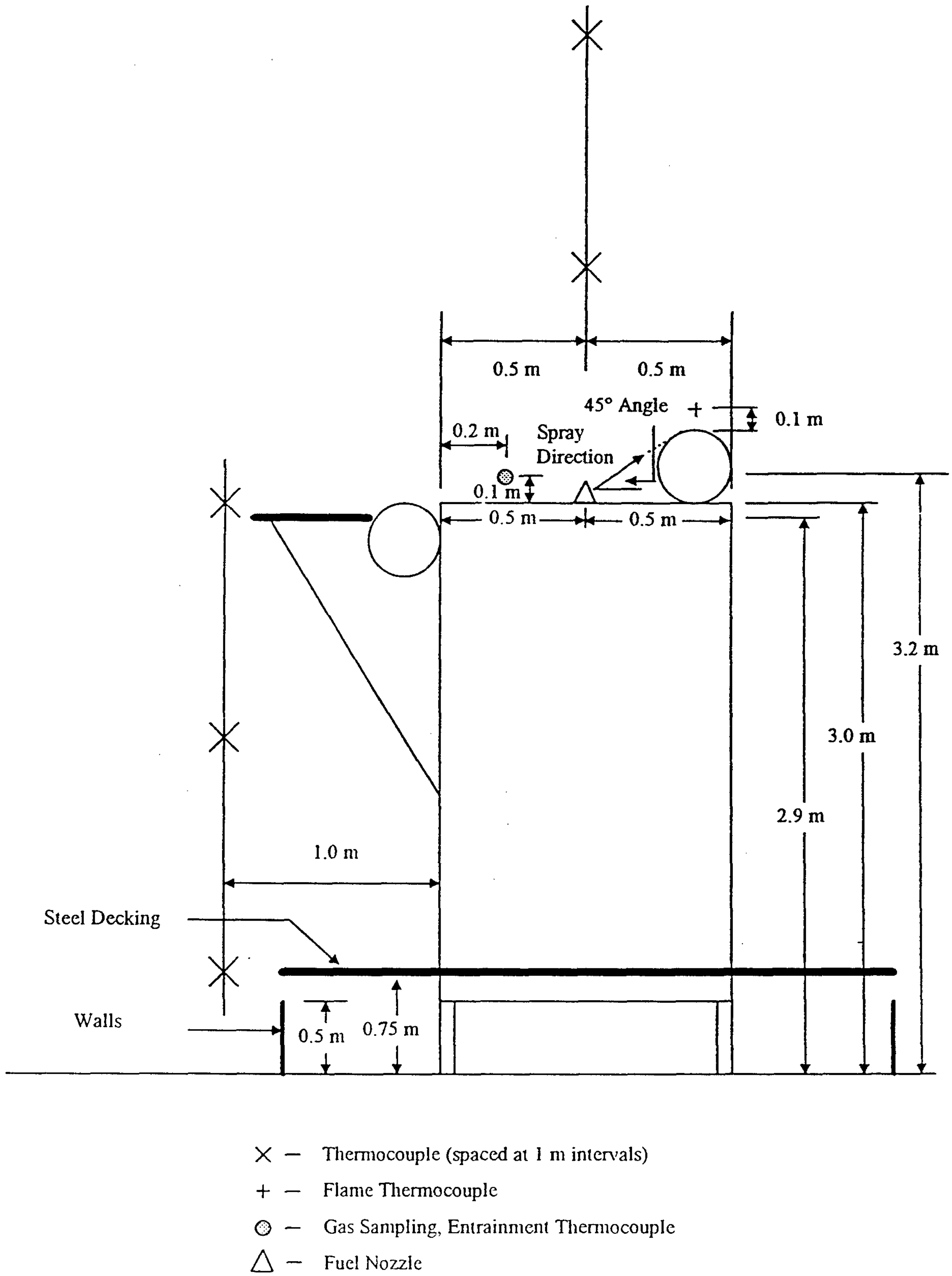


Figure 10. Instrumentation Layout B - West Side

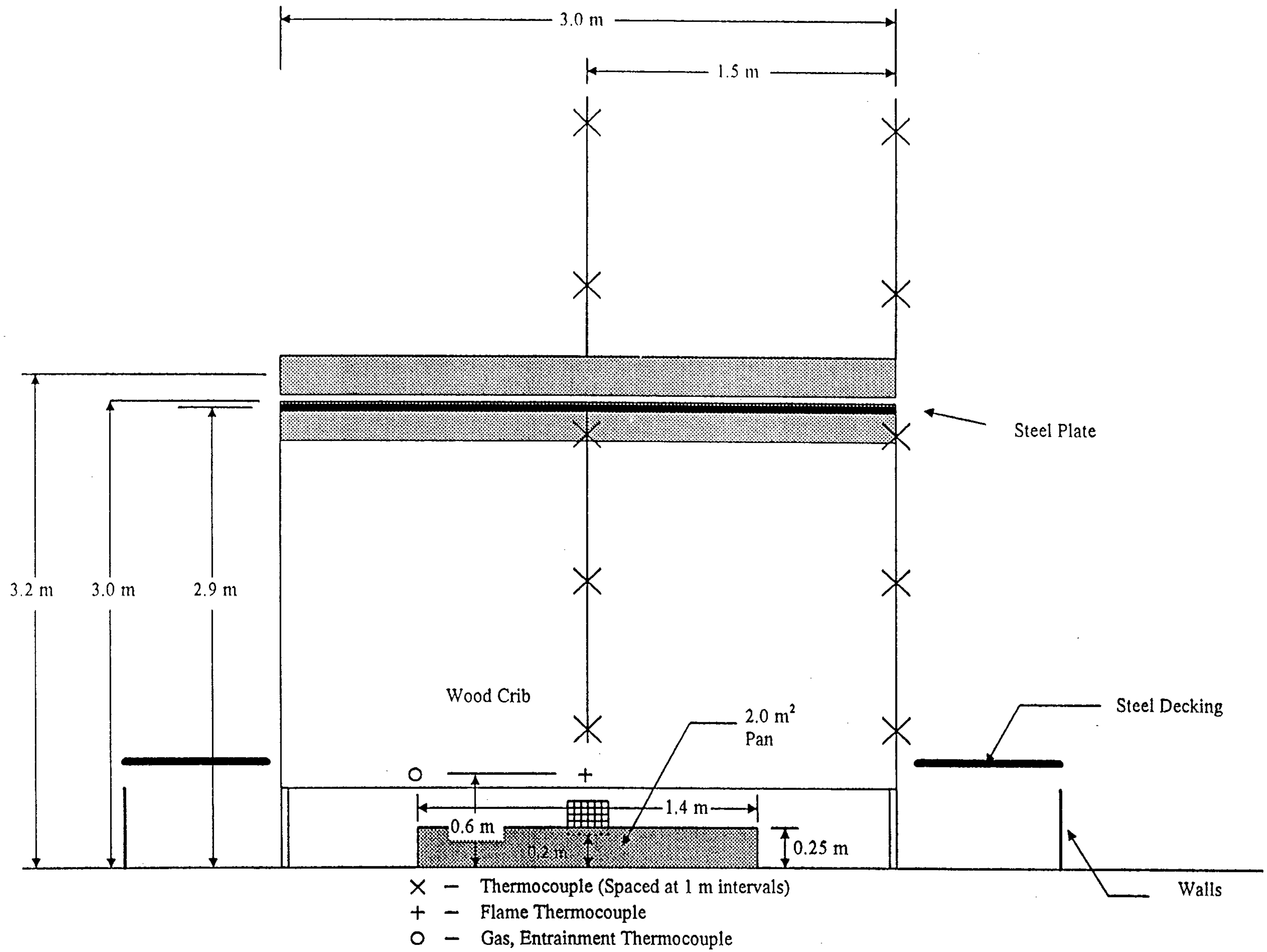


Figure 11. Instrumentation Layout C - North Side

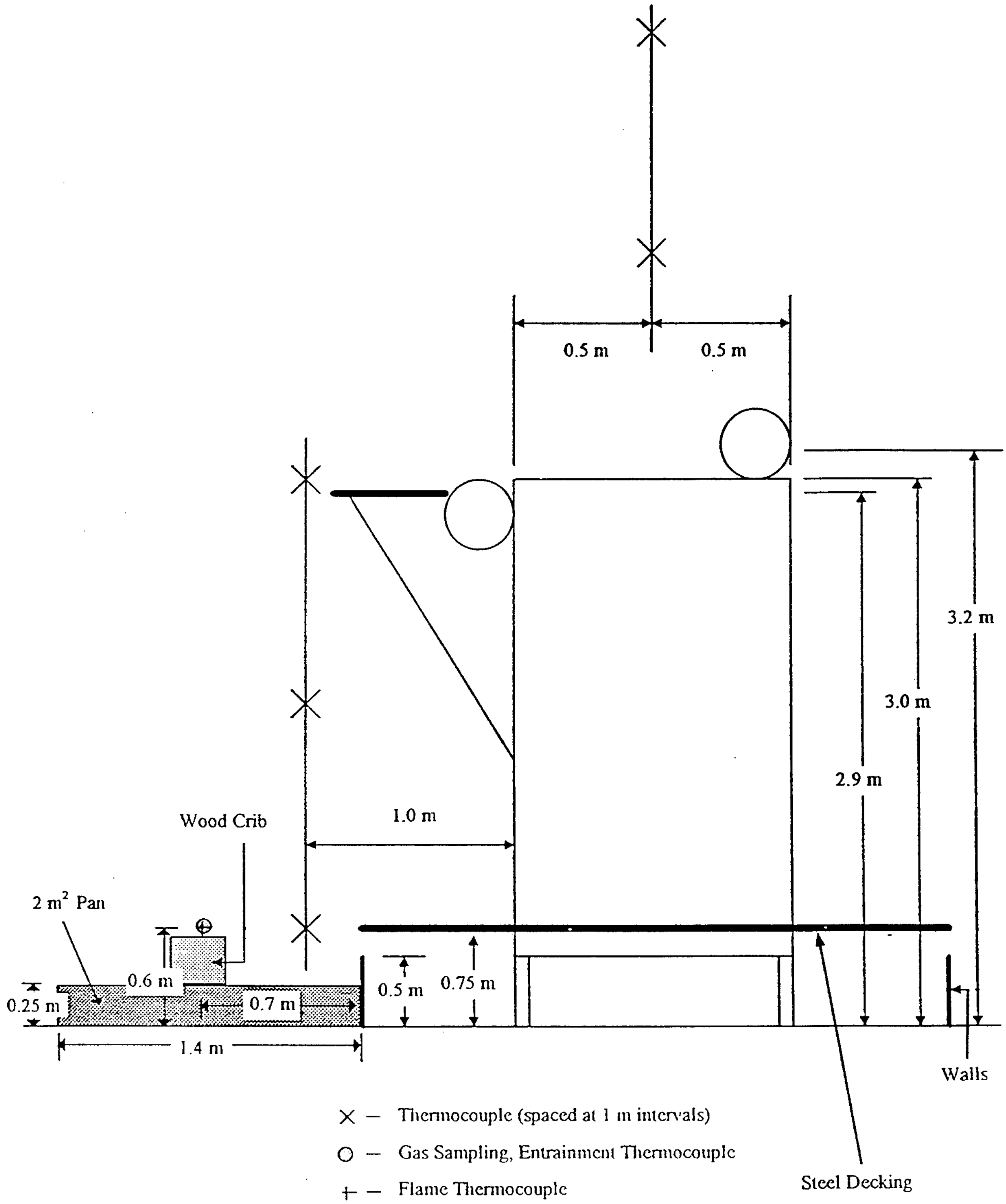
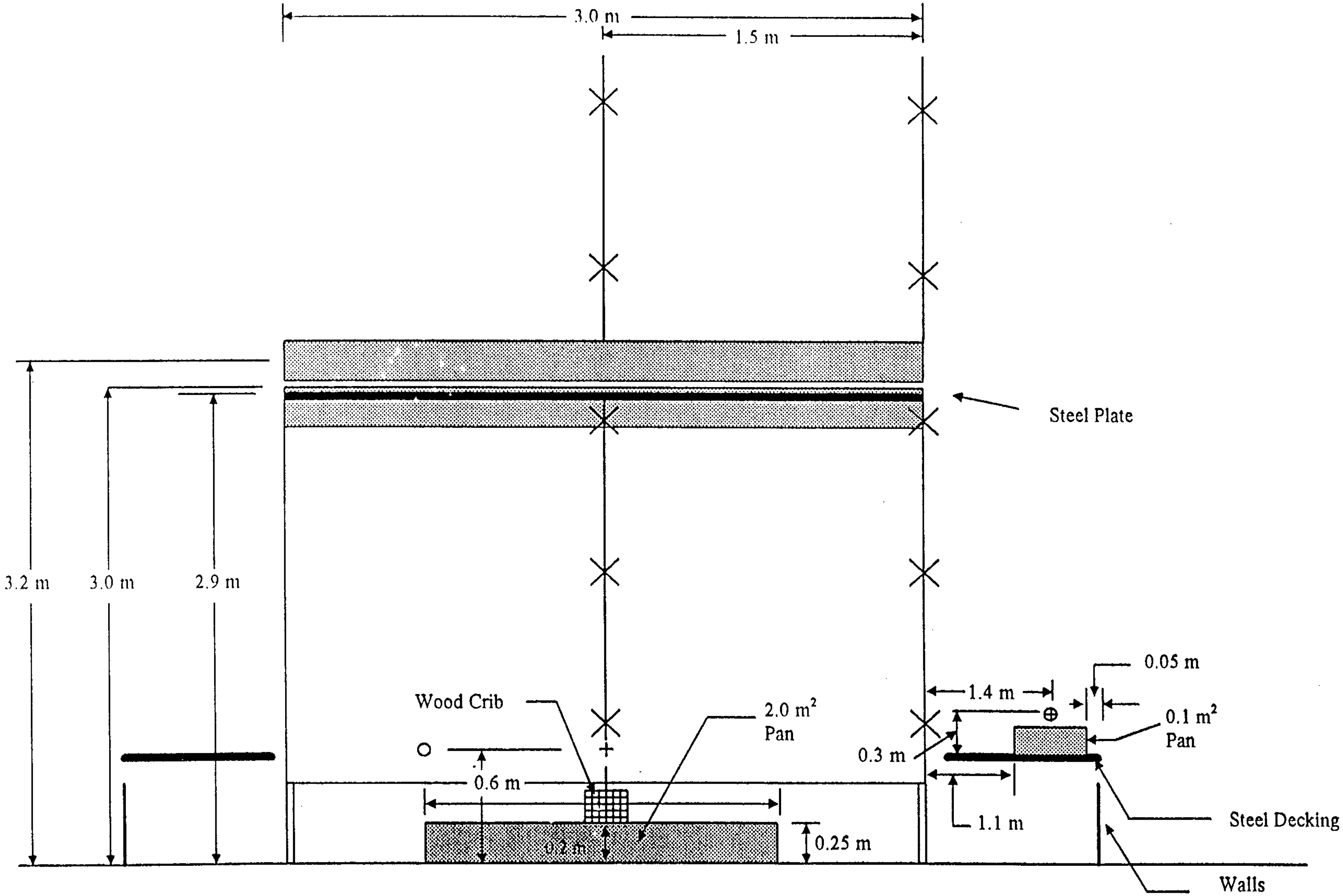


Figure 12. Instrumentation Layout C - West Side



× – Thermocouple (Spaced at 1 m intervals)
○ – Gas, Entrainment Thermocouple
+ – Flame Thermocouple
⊕ – Pan Thermocouple

Figure 13. Instrumentation Layout D - North Side

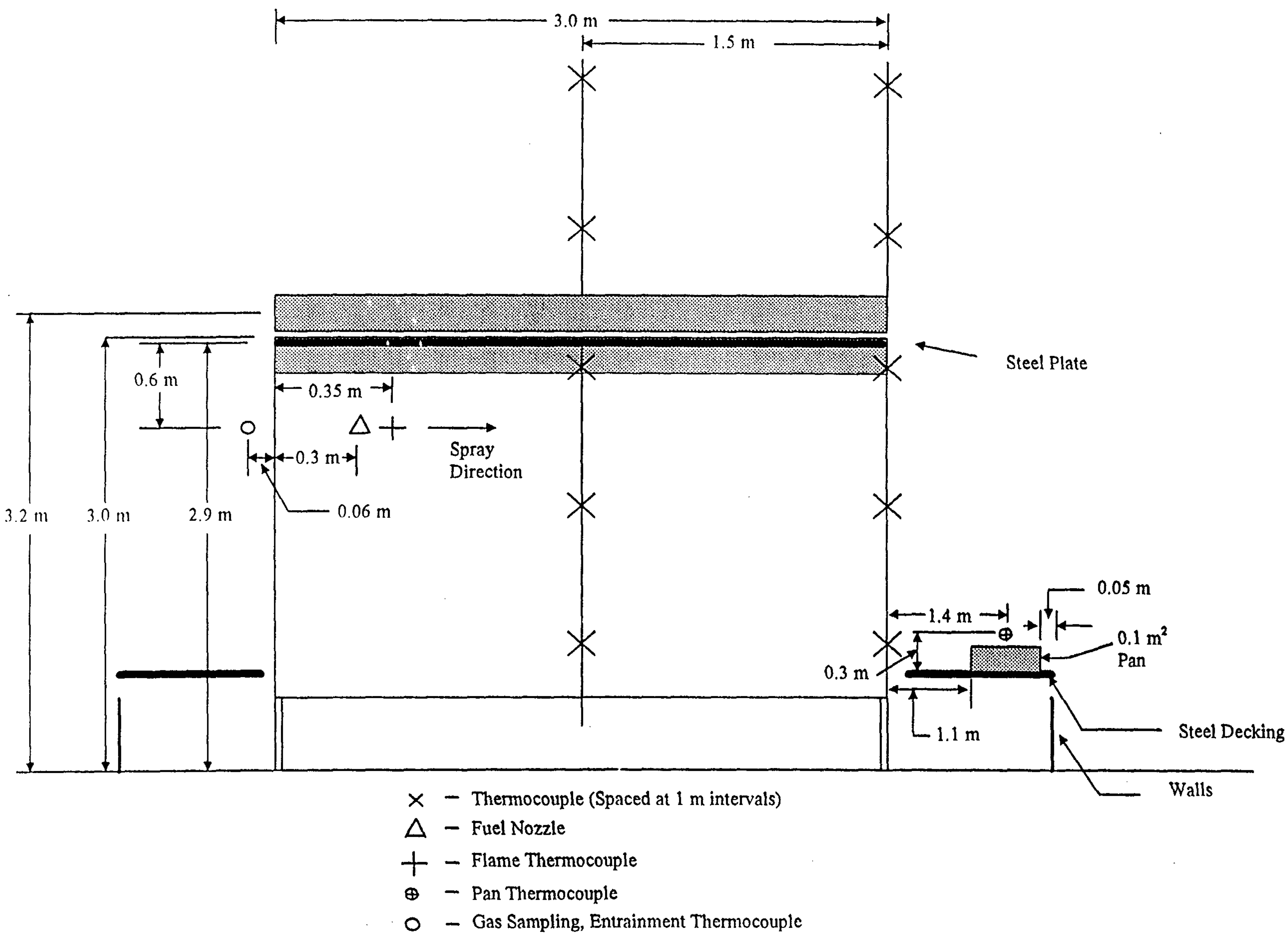


Figure 14. Instrumentation Layout E - North Side

times were used for crib fires. The preburn time for the high pressure nozzles was approximately 40 s, corresponding to the time for the desired nozzle pressure to be achieved and water to reach the nozzles. Fire tests typically continued for fifteen minutes unless extinguishment occurred. In some instances, the fire test was ended earlier to avoid damage to the test facility when no impact on the fire by the water mist was observed. At this time water and fuel discharge were discontinued. After each fire test, fuel trays were checked to assure that extinguishment had not occurred due to fuel depletion.

VI

RESULTS AND DISCUSSION

The extinguishment times of all fire tests are included in Tables 4 through 6. Table 4 lists the fire tests in which the Grinnell AM-10 nozzles were installed and no ceiling or walls were used as specified in the IMO fire tests for Class II and Class III engine rooms[1]. In Tests 1 through 6, 36 nozzles were installed at 1.5 m spacing. In Tests 1 and 2, the operating pressure was 1.2 MPa, and the flow at each nozzle was 12 lpm. In neither test did extinguishment occur during the 15 minutes of the test. In the following tests, the operating pressure was increased to 1.5 MPa. However, the fires were still not extinguished. (Note that Test 4 was aborted due to a piping failure). Figure 15 shows the flame temperature during Test 1. Clearly, the fire was not significantly affected by the mist. Oxygen and carbon dioxide concentrations of entrained air are shown in Figure 16. Again, no significant impact of the mist on the surrounding flame environment is shown. These results are typical for all of the testing listed in Tables 4 and 5. (Data for all tests are given in the Appendix. The data presented include gas temperatures at a 5 m elevation, which are typically near ambient because the plumes of the fire did not intercept their locations.) Carbon monoxide concentrations, not reported in the Appendix, were low throughout the program. In tests without walls the maximum concentration was 744 ppm, except for Test 9, in which the flame fluctuated across the gas sampling location, resulting in a maximum concentration of 1.5%. In Tests 7 through 9, the number of Grinnell nozzles was increased to 100 over a coverage area of 232 m^2. The test results showed no improvement over those in which only 36 nozzles were installed.

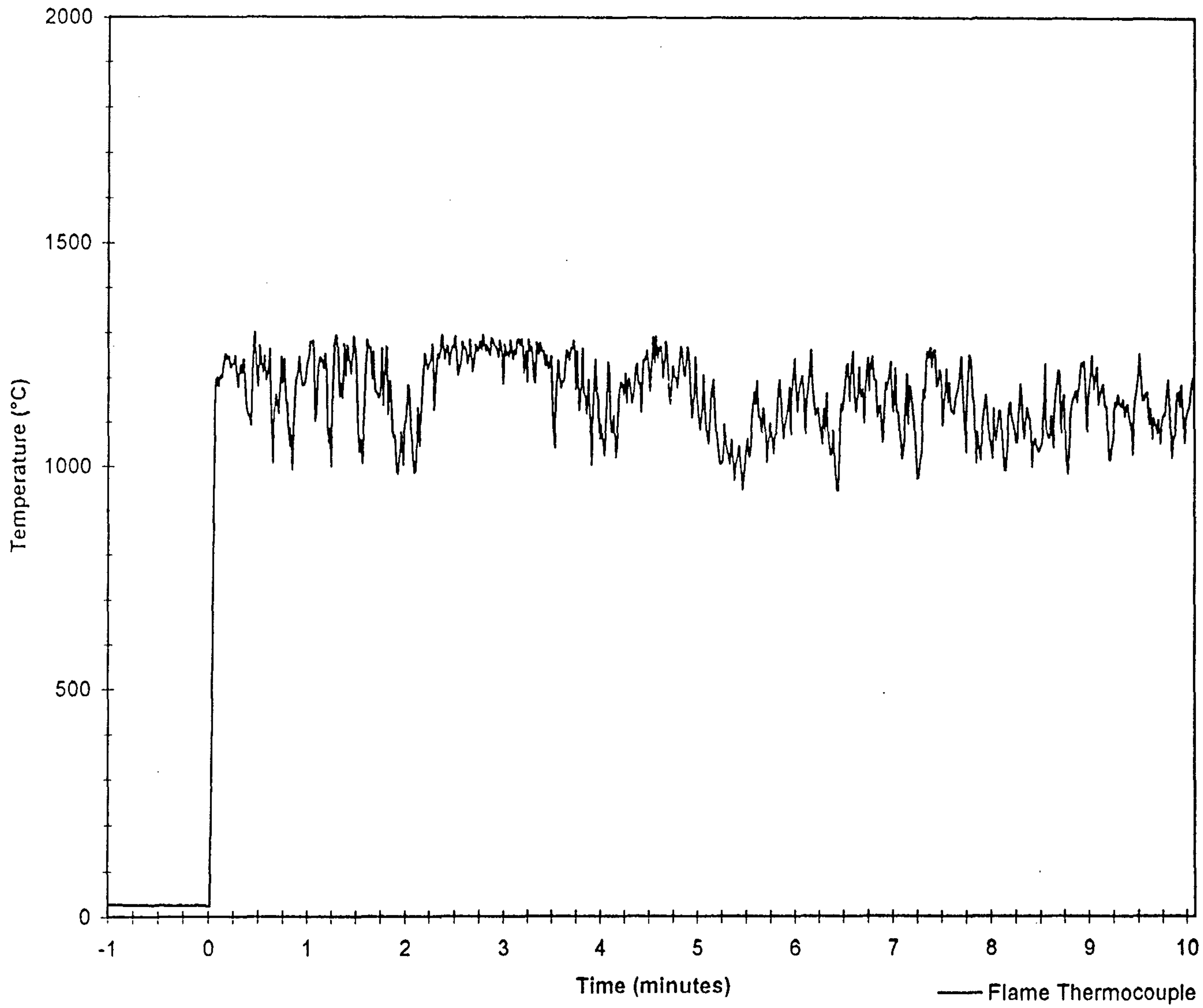


Figure 15. Flame temperature in shielded 1 MW diesel spray fire (Test 1) with Grinnell AM-10 mist nozzle

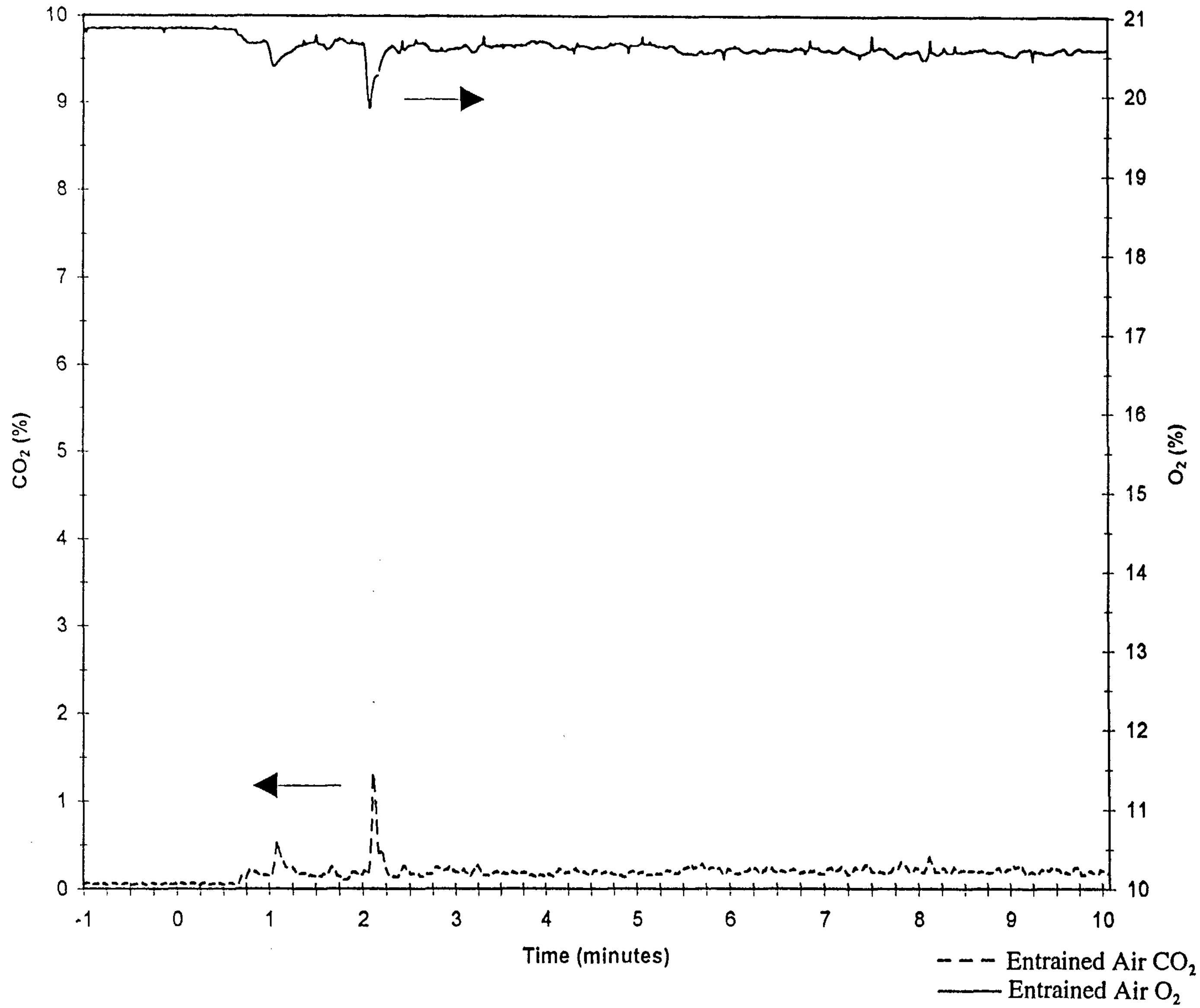


Figure 16. Oxygen and carbon dioxide concentrations adjacent to shielded 1 MW diesel spray fire (Test 1) with Grinnell AM-10 nozzle

Table 5 includes the extinguishment results using the seven-nozzle Spraying Systems prototype. The operating pressure was approximately 6.9 MPa and the flow rate was approximately 5.3 lpm per head. Fires were not extinguished in Tests 10 through 16. As in the tests with the Grinnell nozzles, the fire was not significantly affected by the mist whether 36 or 90 nozzles were installed. The results of Tests 1 through 16 indicate that it is unlikely that current mist technology, as represented by the two systems used in the program[1], will be able to extinguish fires in the current IMO fire test protocol for Class II and Class III engines. It is noteworthy that the spray patterns of the mist nozzles were not as well developed compared to observed patterns when the nozzles have been installed under ceilings[4,5]. Compared to the normal installation under ceiling, adjacent spray patterns did not overlap. Presumably this was due to the ability of the nozzles to entrain air from above.

In order to investigate the capabilities of the selected mist systems, a series of seven fire tests were conducted using one of two installations: 1) a ceiling alone, or 2) a ceiling with walls formed by tarpaulins.

The extinguishment results of these tests are included in Table 6. These tests were conducted with the Spraying Systems prototype operating at 6.9 MPa and a flow rate of about 5.3 lpm per head. In Tests 17 and 18, a ceiling was constructed directly above the branchline pipes. This improved the discharge pattern of the nozzles in that there was overlap between the sprays from adjacent nozzles. Despite this improvement, no fires were extinguished and the results were similar to those shown in Figures 15 and 16. It is concluded from these two tests that fire test results in smaller enclosures cannot be extrapolated to larger enclosures with "unconfined ceilings."

In Tests 19 and 20, a 940 m^3 enclosure was formed using the previously installed ceiling and installing tarpaulins for walls. A 4 m^2 vent was installed similar to that provided for in the IMO fire tests for 500 m^3 enclosures. Extinguishment occurred in Test 19 with a 6 MW diesel spray on top of the engine mock-up. Flame temperature as a function of time is shown in Figure 17 and the oxygen and carbon dioxide concentrations are shown in Figure 18. Extinguishment occurred in 3.5 min when the oxygen concentration was about 18%.

In Test 20 when the 6 MW diesel spray fire was shielded on the side of the mock-up, the fire was not extinguished. The flame temperature, similar to that shown in Figure 15, suggests that the

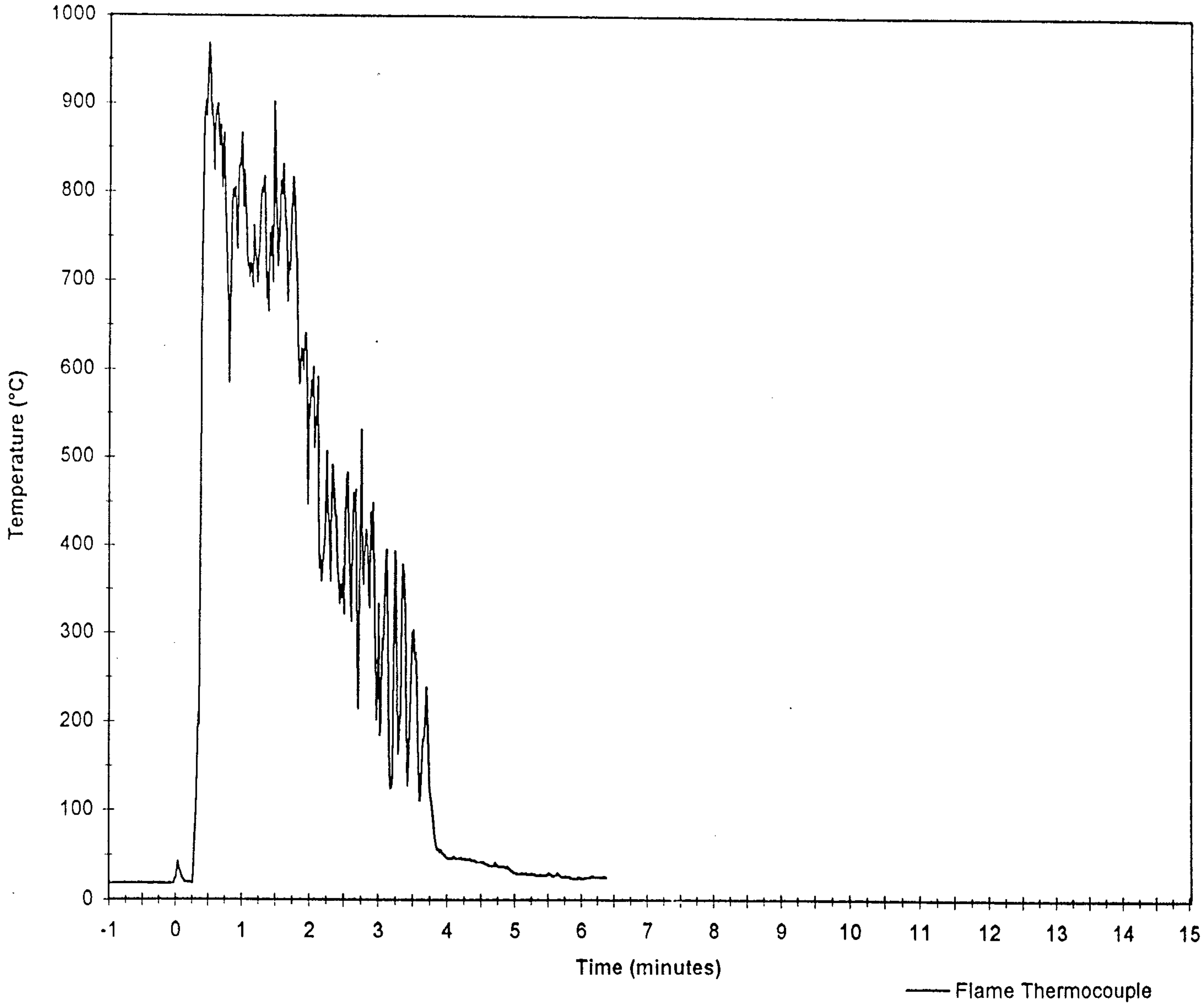


Figure 17. Flame temperature in a 6 MW diesel spray fire (Test 19) with Spraying Systems seven-nozzle head

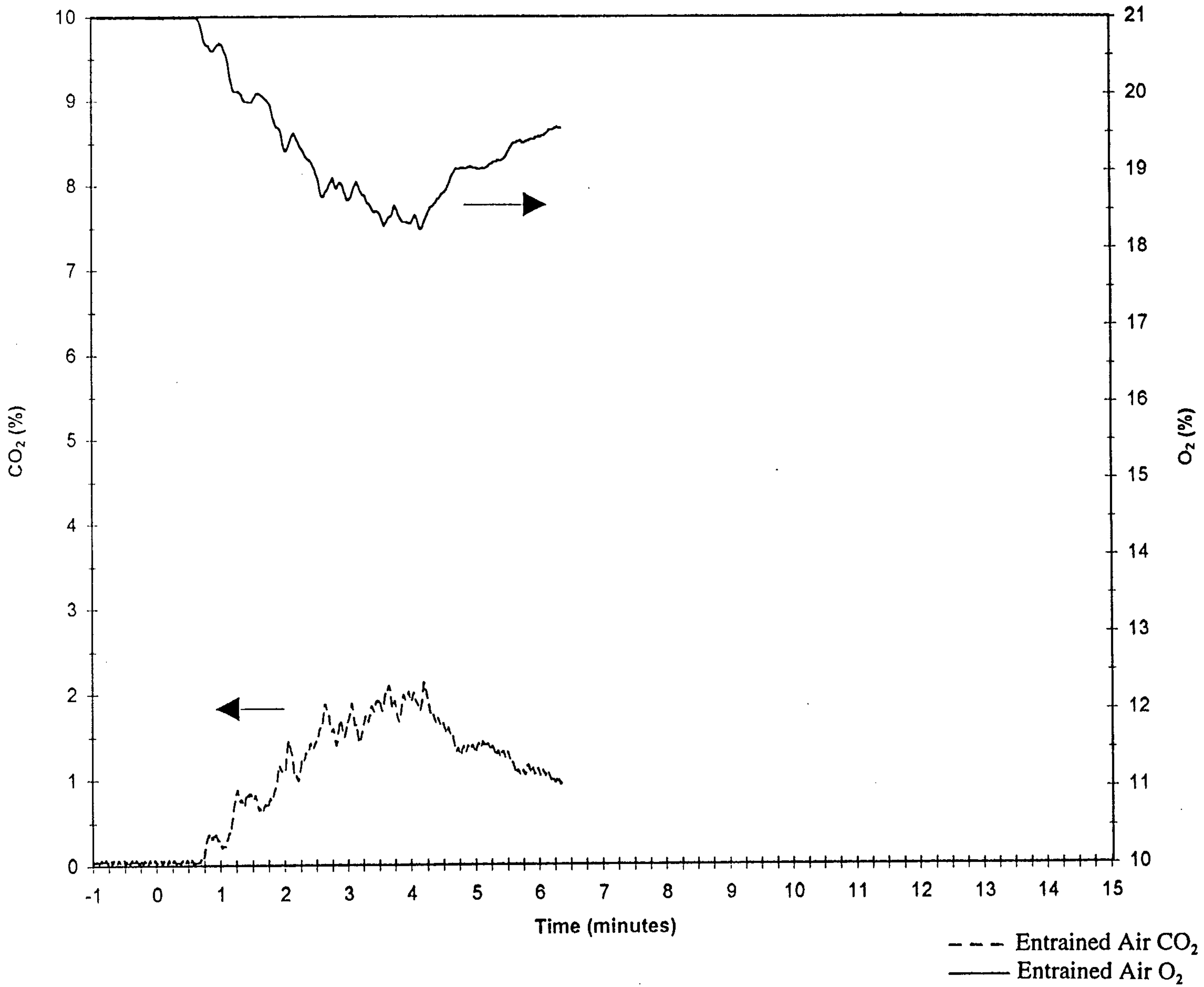


Figure 18. Oxygen and carbon dioxide concentrations adjacent to a 6 MW diesel spray fire (Test 19) with Spraying Systems seven-nozzle head

fire was not significantly affected by the mist. The oxygen concentration, shown in Figure 19 along with the carbon dioxide concentration, decreased during the test to a minimum of about 18.5%, reaching a plateau at that point. The oxygen concentration did not continue to decrease due to the venting and leakage from the ceiling and walls.

In Tests 21 through 23, the vent to the enclosure was covered. In Test 21, which included a 6 MW shielded diesel spray fire and a 0.1 m^2 heptane pool fire, the shielded spray fire was extinguished in about 5 min when the oxygen concentration was about 16.5%. The 0.1 m^2 heptane pool, placed on the top of the bilge plate, 0.75 m off the floor, was also extinguished in about 2.75 min. Flame temperatures are shown in Figure 20 and oxygen and carbon dioxide concentrations are shown in Figure 21. The results of this test indicate that water mist systems can extinguish large shielded spray fires when ventilation is controlled and significant oxygen depletion occurs. The extinguishment of the small pool fire suggests that in this scenario, fires would be extinguished at any location in the volume. The fire extinguishment in Test 21, in contrast to Test 20, suggests that oxygen depletion is a significant part of the mist extinguishment process in addition to such mechanisms as flame cooling, local displacement of oxygen through the generation of steam, and flame destabilization.

In Tests 22 and 23, in which smaller fire sources were used, extinguishment did not occur. In Test 22, a 0.1 m^2 heptane pool fire was used as the sole fire source (see location of fire in Figure 14). The fire swayed significantly due to interaction with the mist, as indicated by fluctuations in the output of the flame thermocouple in Figure 22. Note that the mist system was shut off at 22 min. The oxygen and carbon dioxide concentrations measured adjacent to the pool fire, as shown in Figure 23, probably indicate passage of the fire across the gas sampling line. In Test 23, both the shielded 1 MW diesel spray fire and a 0.1 m^2 heptane pan were used as fuel sources, as shown in Figure 14. The flame temperatures were not significantly affected by the mist despite the oxygen level decreasing to 17.6% (Figure 24). The oxygen concentration plateaued in this test at 17.6% due to leaks in the enclosure. In Tests 19 through 23, carbon monoxide concentrations were higher than in the previous. The maxima were 2338, 1319, 2803, 3794, and 2565 ppm, respectively.

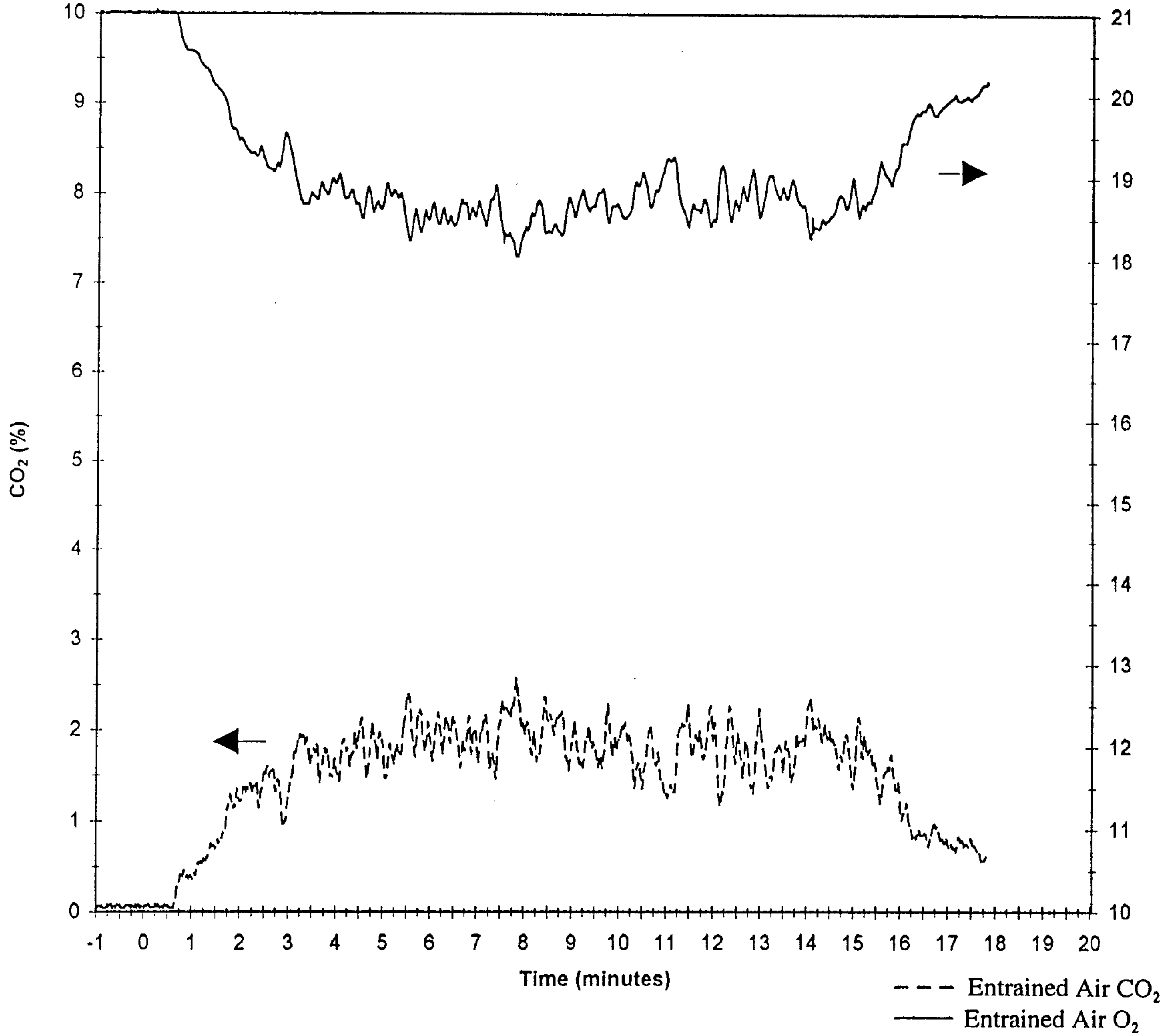


Figure 19. Oxygen and carbon dioxide concentrations adjacent to a 6 MW shielded diesel spray fire (Test 20) with Spraying Systems seven-nozzle head

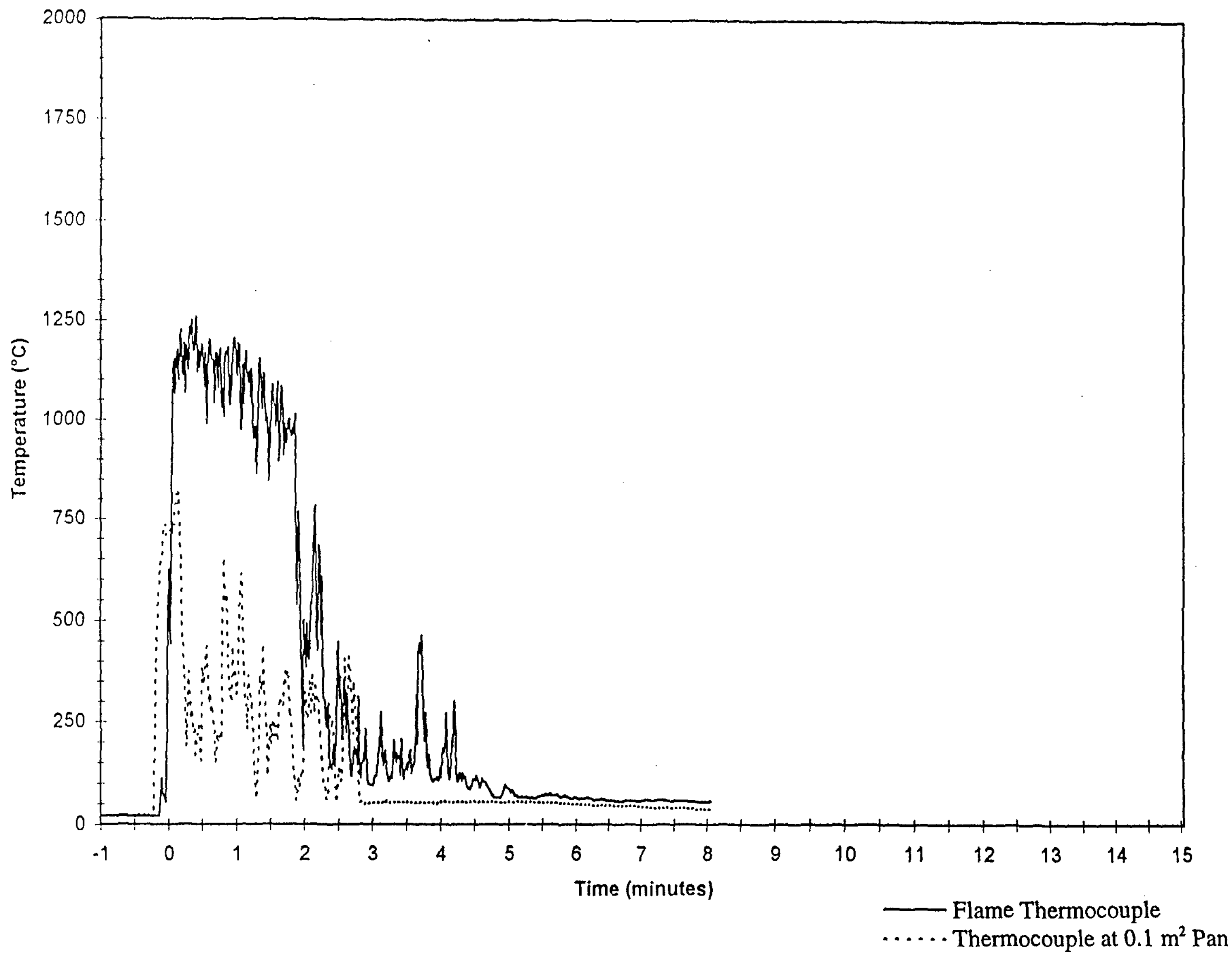


Figure 20. Flame temperatures in a 6 MW shielded diesel spray fire and a 0.1 m^2 heptane pool fire (Test 21) with Spraying Systems seven-nozzle head

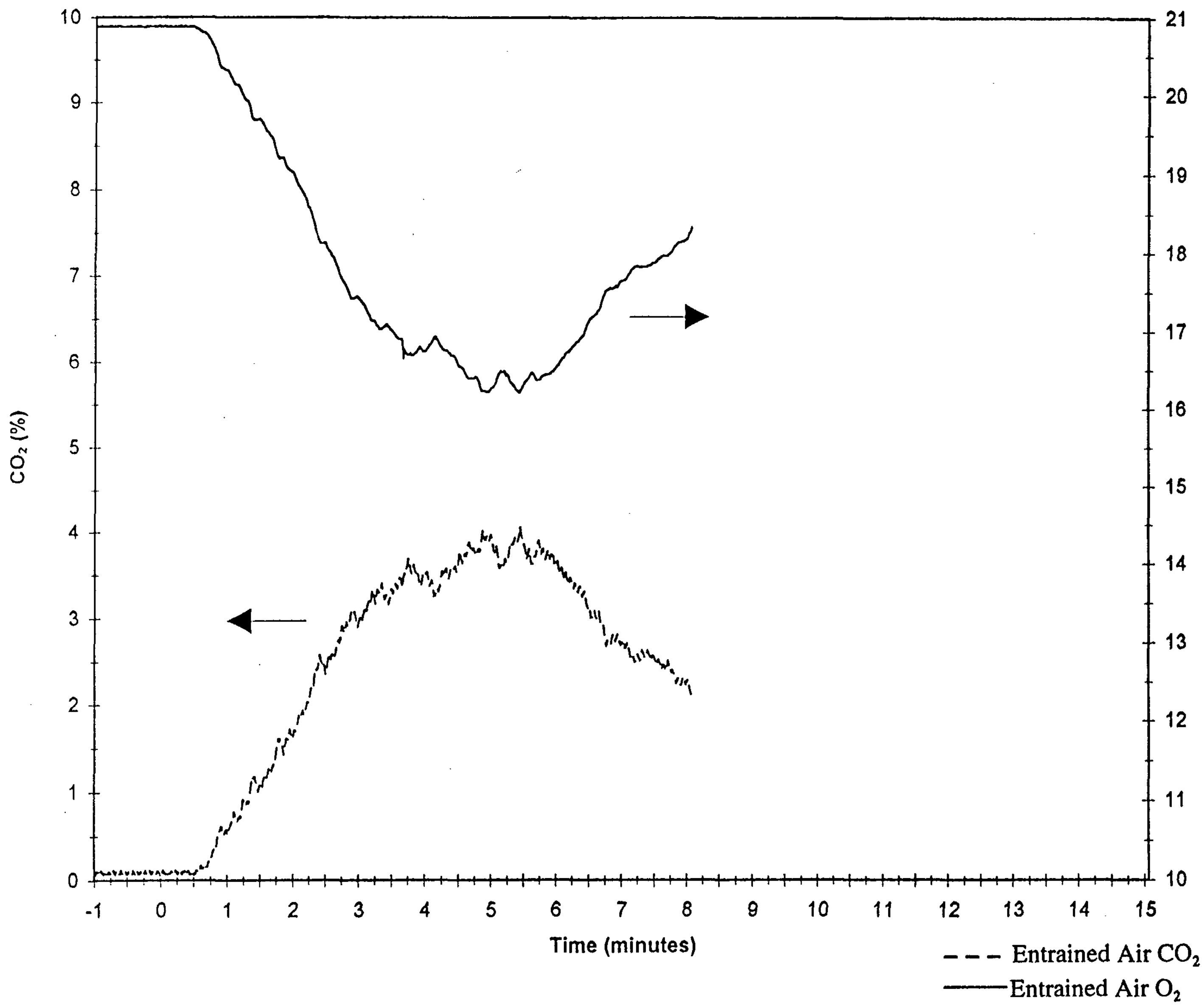


Figure 21. Oxygen and carbon dioxide concentrations adjacent to a 6 MW shielded diesel spray fire (Test 21) with Spraying Systems seven-nozzle head

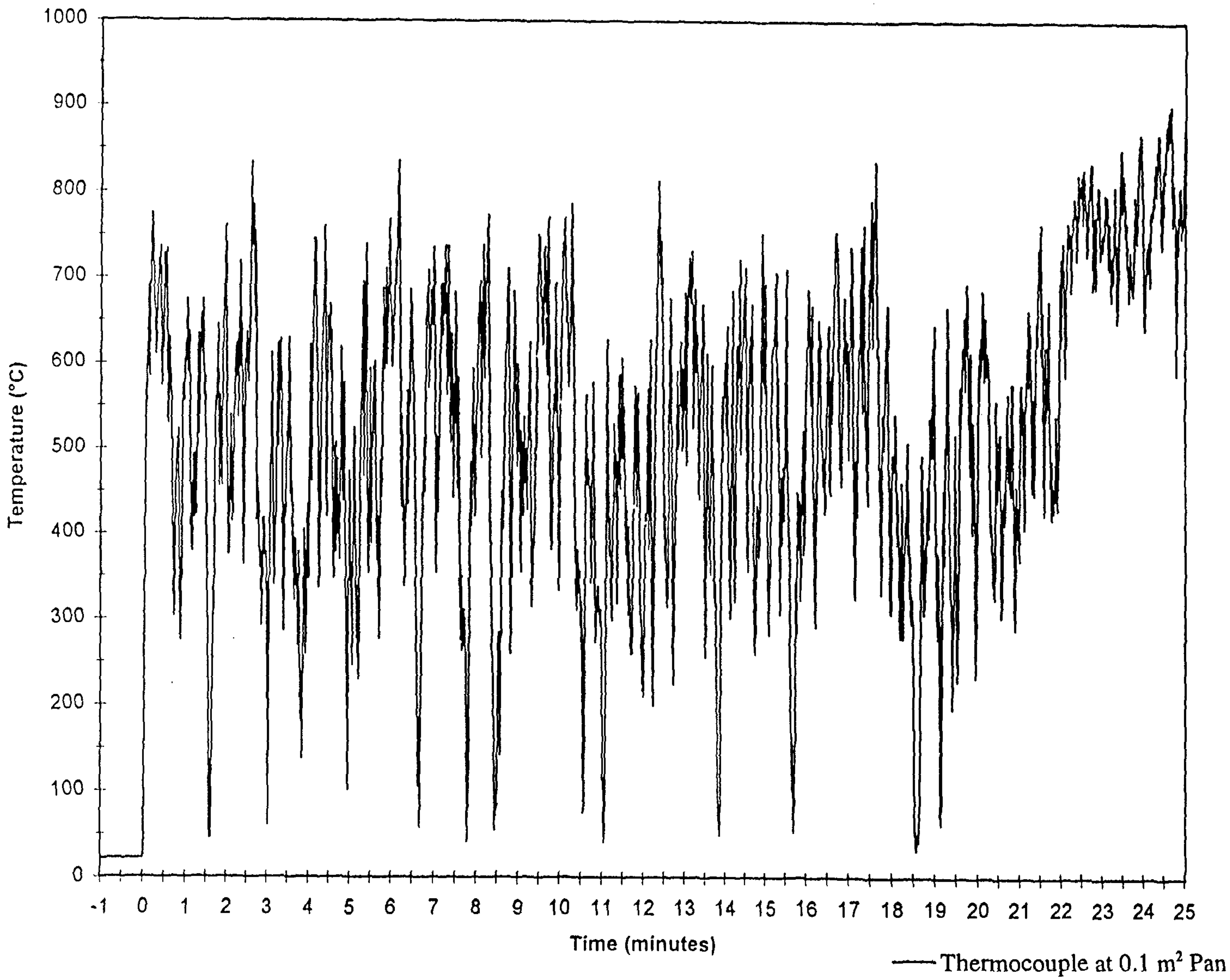


Figure 22. Flame temperatures in a 0.1 m^2 MW heptane pool fire (Test 22) with Spraying Systems seven-nozzle head

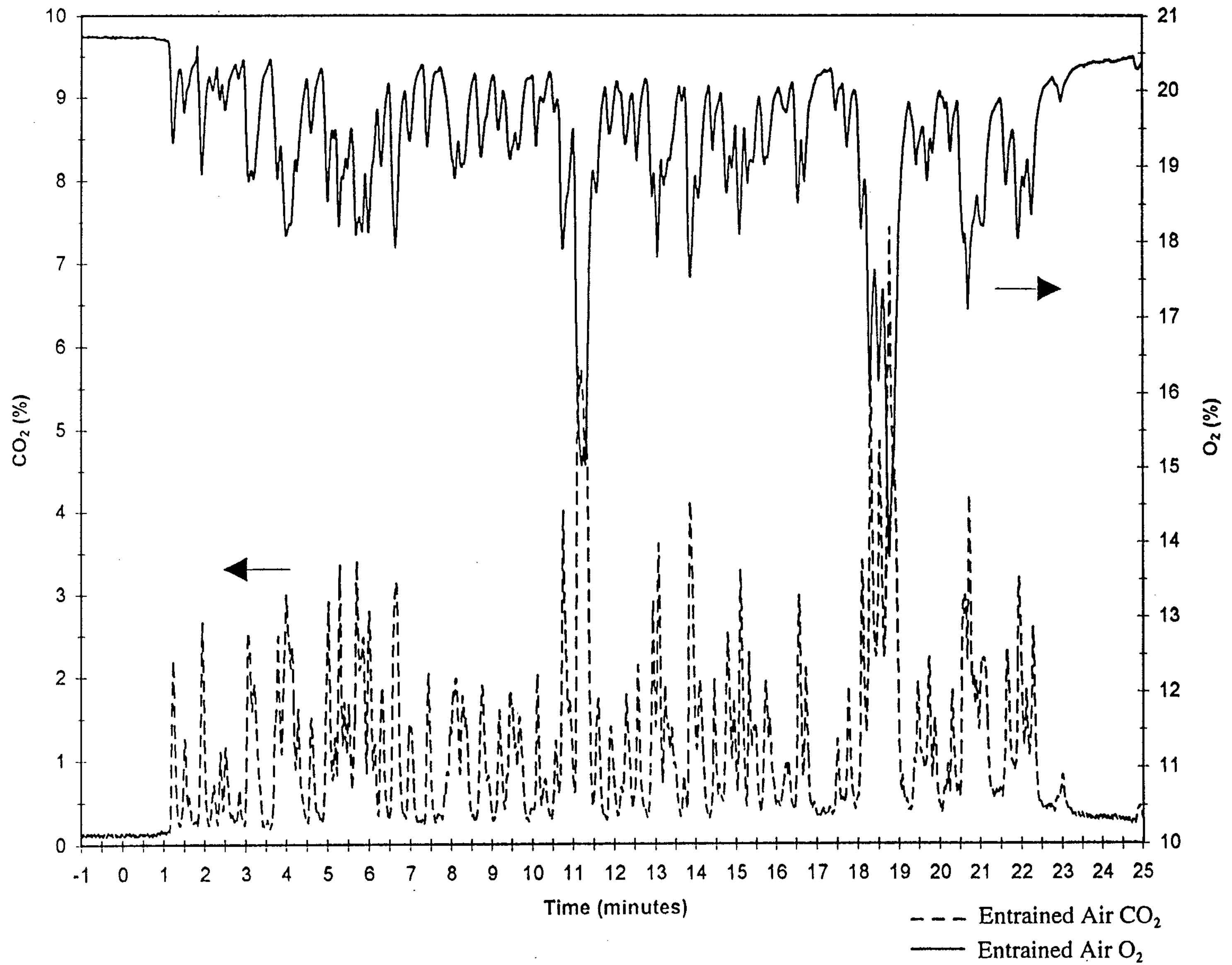


Figure 23. Oxygen and carbon dioxide concentrations adjacent to a 0.1 m[2] heptane pool fire (Test 22) with Spraying Systems seven-nozzle head

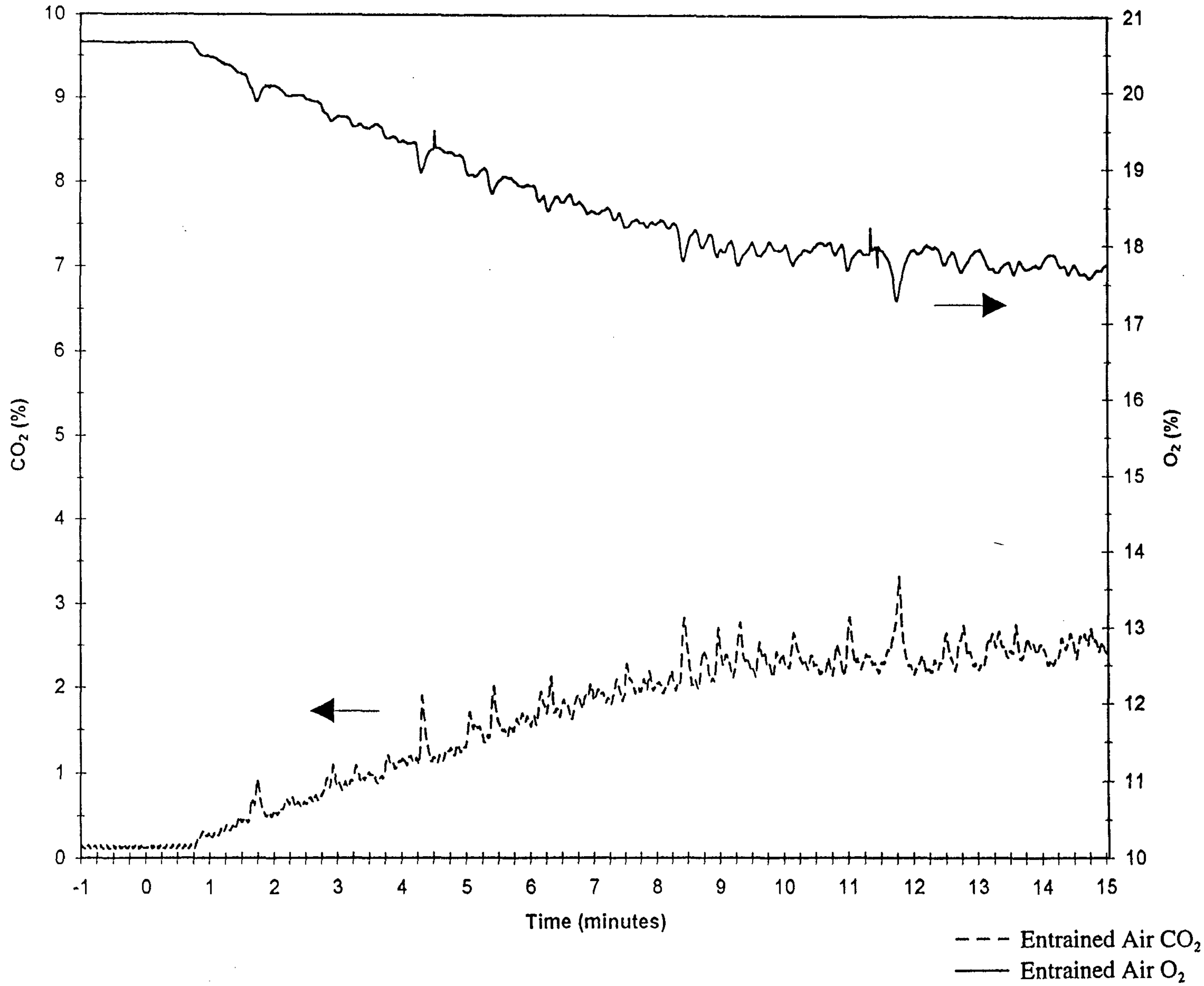


Figure 24. Oxygen and carbon dioxide concentrations adjacent to a 1 MW shielded spray fire (Test 23) with Spraying Systems seven-nozzle head

Because of the failure of the water mist systems in all tests except some in which an enclosure was used, it is recommended that IMO testing be allowed for the largest volume enclosure for which approval is sought. In those tests, realistic ventilation needs to be simulated.

VII

CONCLUSIONS AND RECOMMENDATIONS

1. The results of this test program indicate that current water mist technology, as represented by the two systems used in the test program, is unlikely to be capable of extinguishing test fires in the IMO fire test protocol for Class III engine rooms.

2. Depletion of oxygen by the fire is an important contributing mechanism in the extinguishment of flammable liquid fire by water mist systems.

3. The IMO test protocol developed in 1994 for Class II and Class III engine rooms should be amended to allow manufacturers of water mist systems to test to the largest volume enclosure for which approval is sought. Because ventilation has been found to be important, realistic ventilation conditions must be used in the fire tests with allowed ventilation incorporated in the system listing.

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APPENDIX

FIRE TEST DATA

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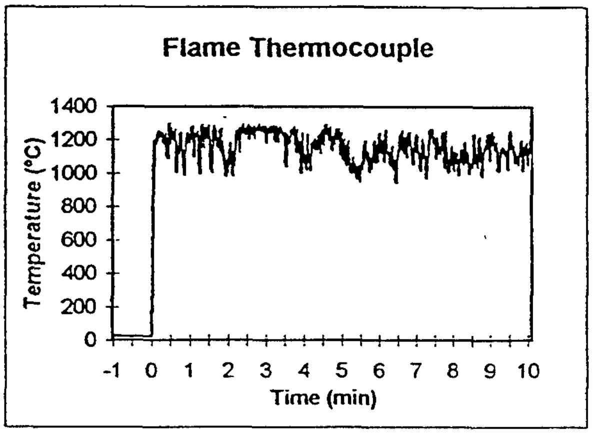
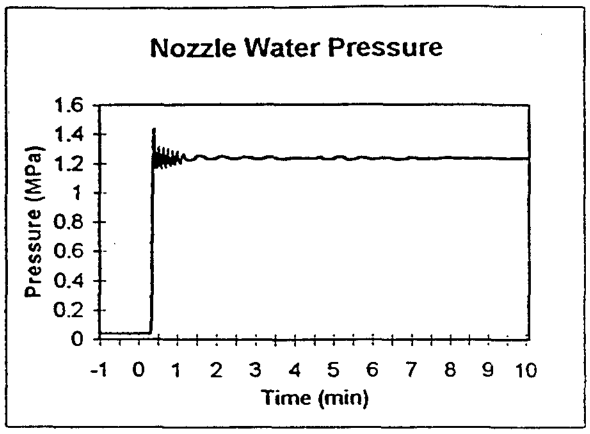
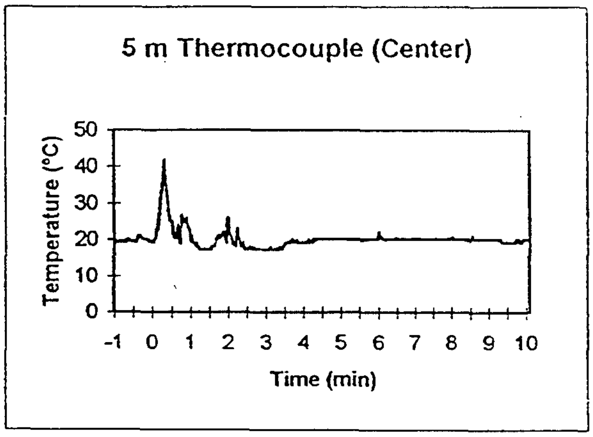
Test 1



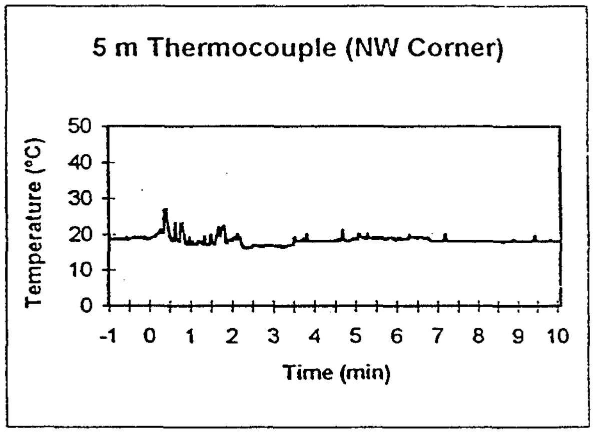
Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1 0 1 2 3 4 5 6 7 8 9 10
Time (min)



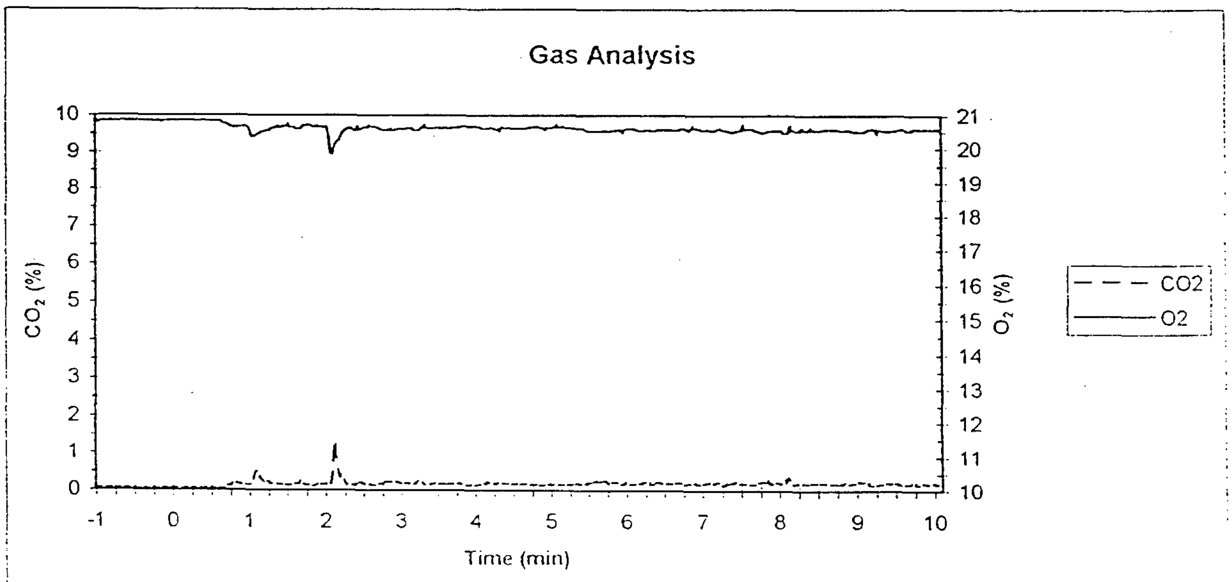
Nozzle Water Pressure
Pressure (MPa)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1 0 1 2 3 4 5 6 7 8 9 10
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
50
40
30
20
10
0
-1 0 1 2 3 4 5 6 7 8 9 10
Time (min)

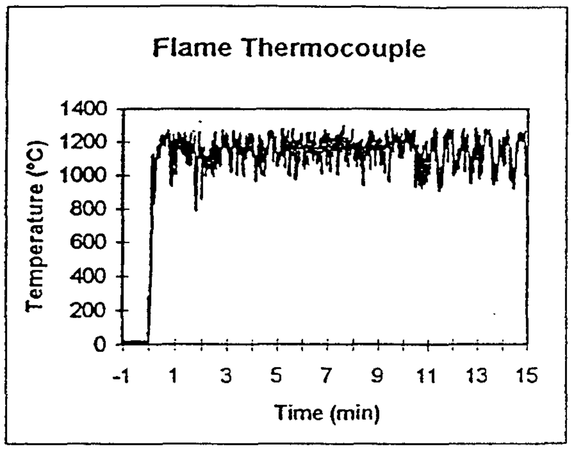


5 m Thermocouple (NW Corner)
Temperature (°C)
50
40
30
20
10
0
-1 0 1 2 3 4 5 6 7 8 9 10
Time (min)

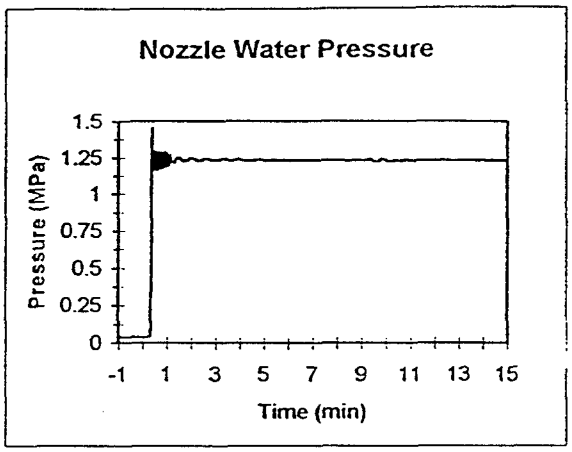


Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
O2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10
Time (min)

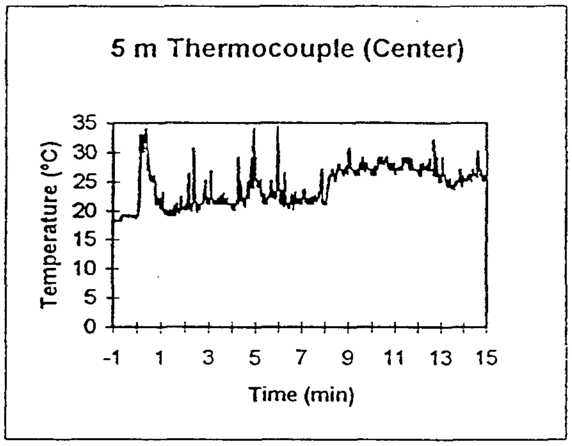
Test 2



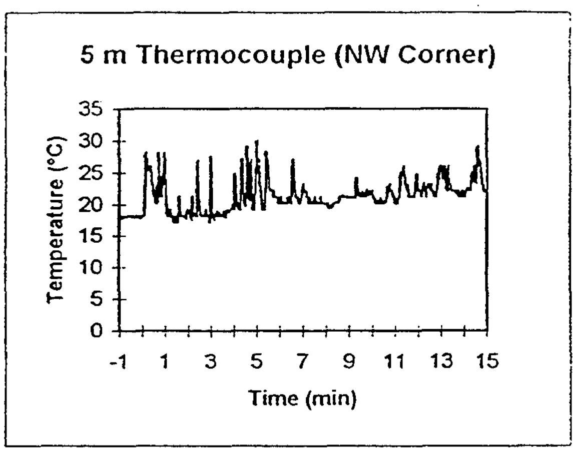
Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1
1
3
5
7
9
11
13
15
Time (min)



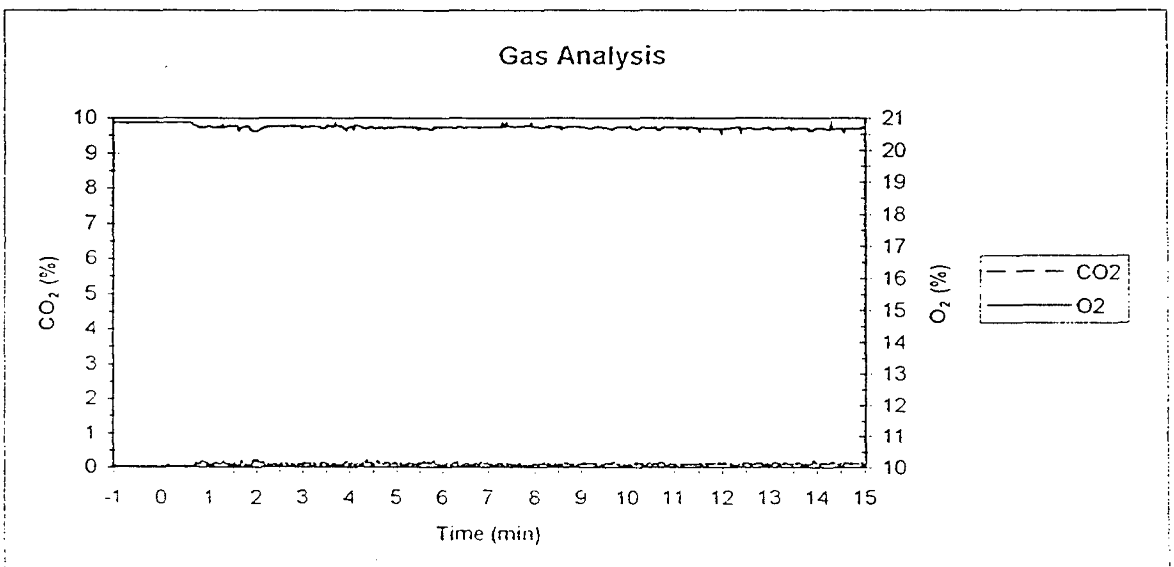
Nozzle Water Pressure
Pressure (MPa)
1.5
1.25
1
0.75
0.5
0.25
0
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
35
30
25
20
15
10
5
0
-1
1
3
5
7
9
11
13
15
Time (min)

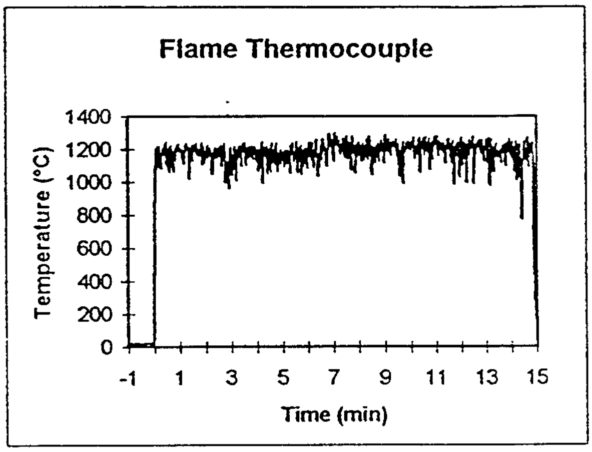


5 m Thermocouple (NW Corner)
Temperature (°C)
35
30
25
20
15
10
5
0
-1
1
3
5
7
9
11
13
15
Time (min)

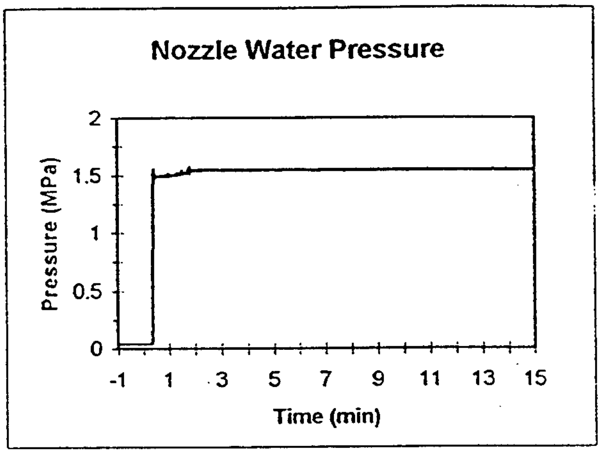


Gas Analysis
CO2 (%)
O2 (%)
10
9
8
7
6
5
4
3
2
1
0
21
20
19
18
17
16
15
14
13
12
11
10
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)
CO2
O2

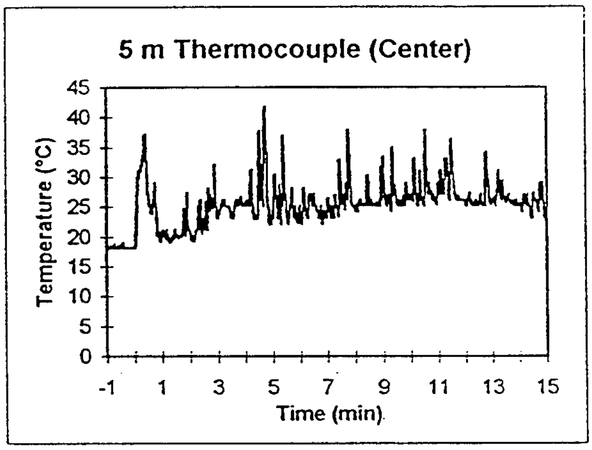
Test 3



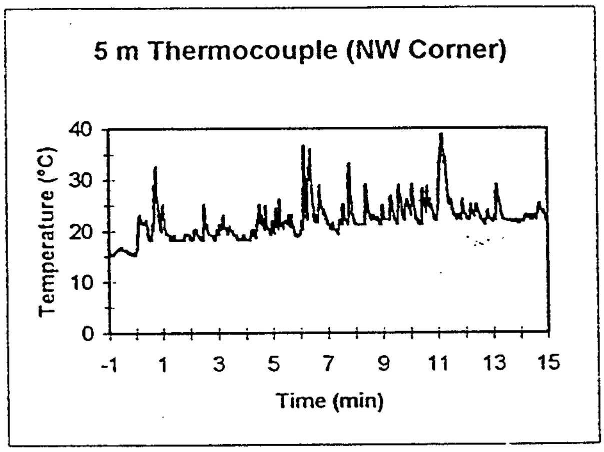
Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1
1
3
5
7
9
11
13
15
Time (min)



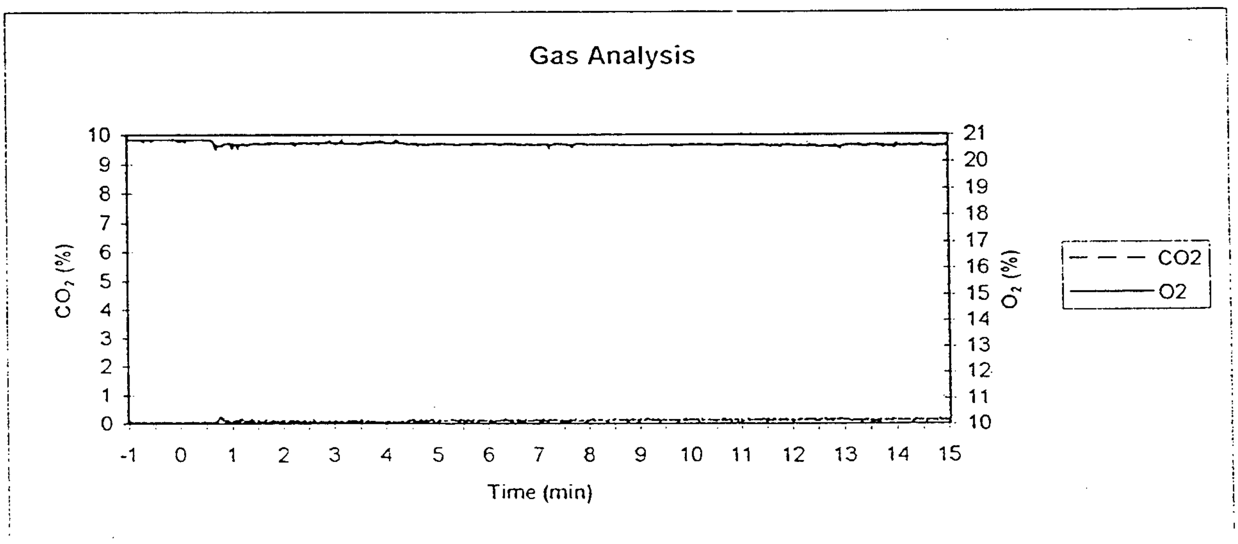
Nozzle Water Pressure
Pressure (MPa)
2
1.5
1
0.5
0
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
45
40
35
30
25
20
15
10
5
0
-1
1
3
5
7
9
11
13
15
Time (min)

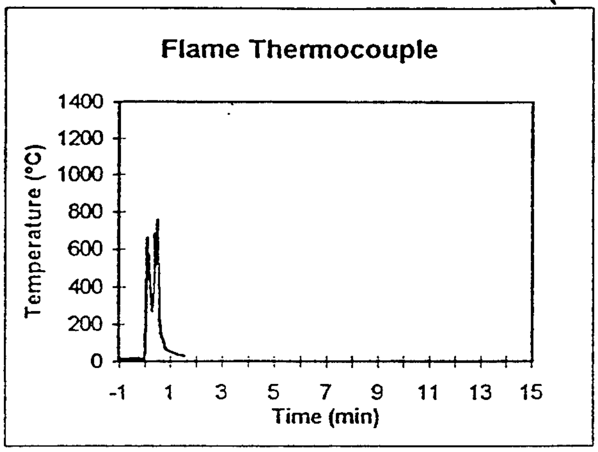


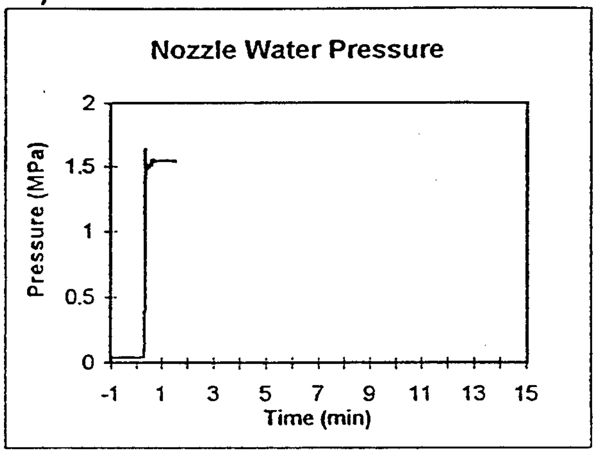
5 m Thermocouple (NW Corner)
Temperature (°C)
40
30
20
10
0
-1
1
3
5
7
9
11
13
15
Time (min)

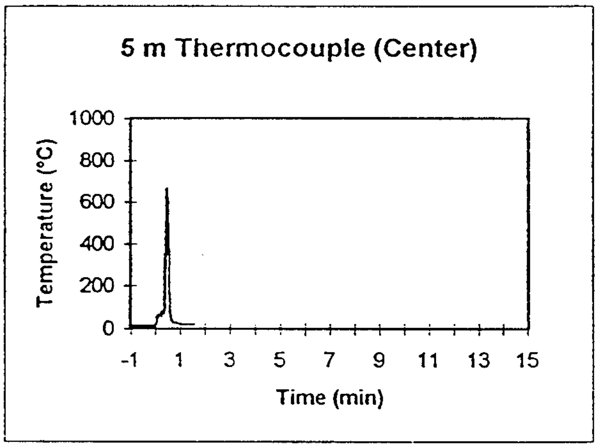


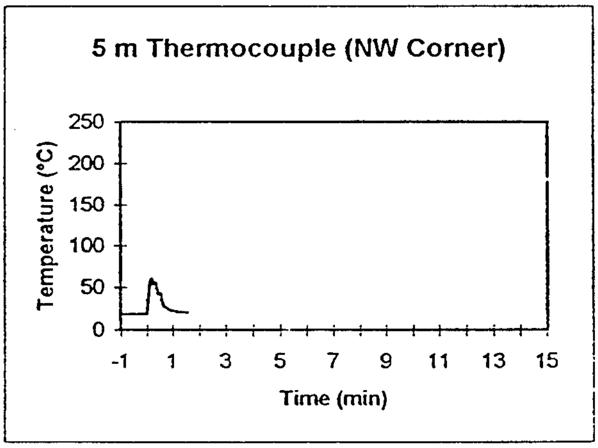
Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
O2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)
CO2
O2

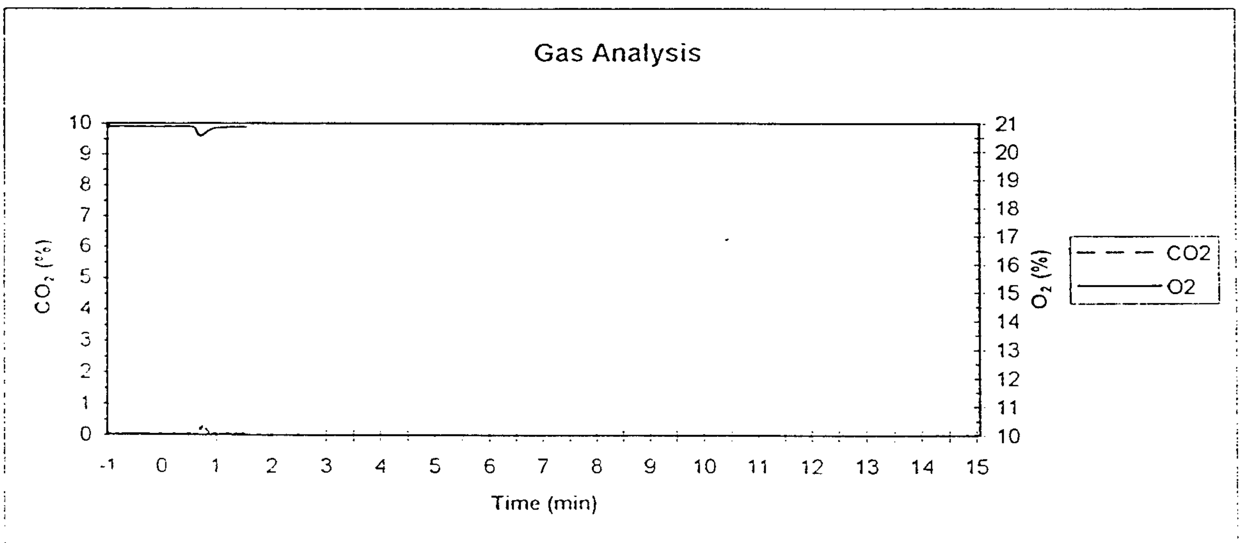
Test 4
(Aborted)



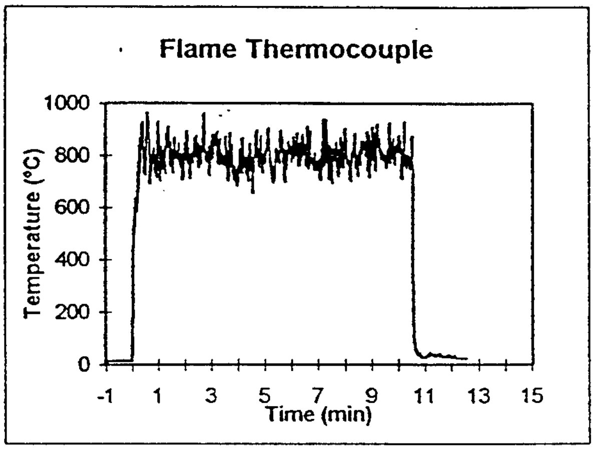




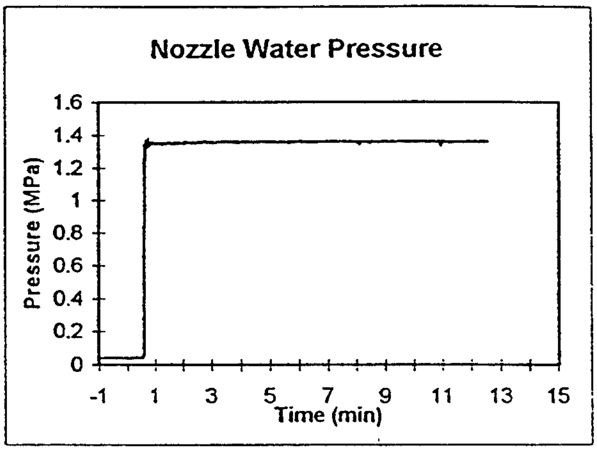




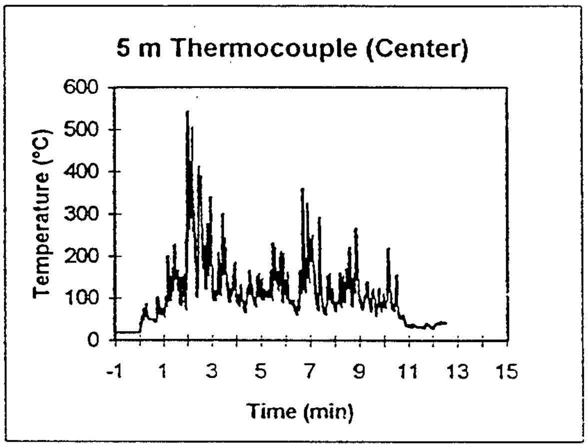
Test 5



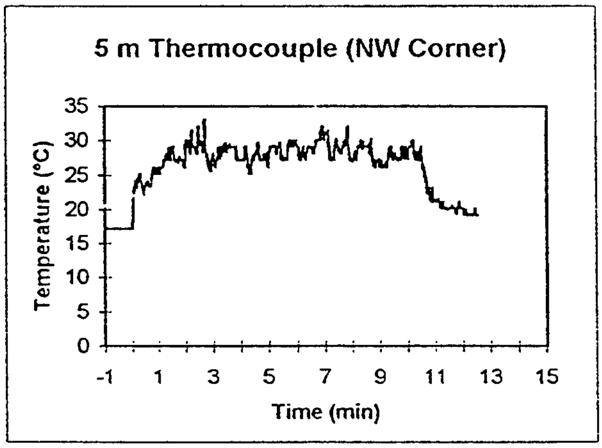
Flame Thermocouple
Temperature (°C)
1000
800
600
400
200
0
-1
1
3
5
7
9
11
13
15
Time (min)



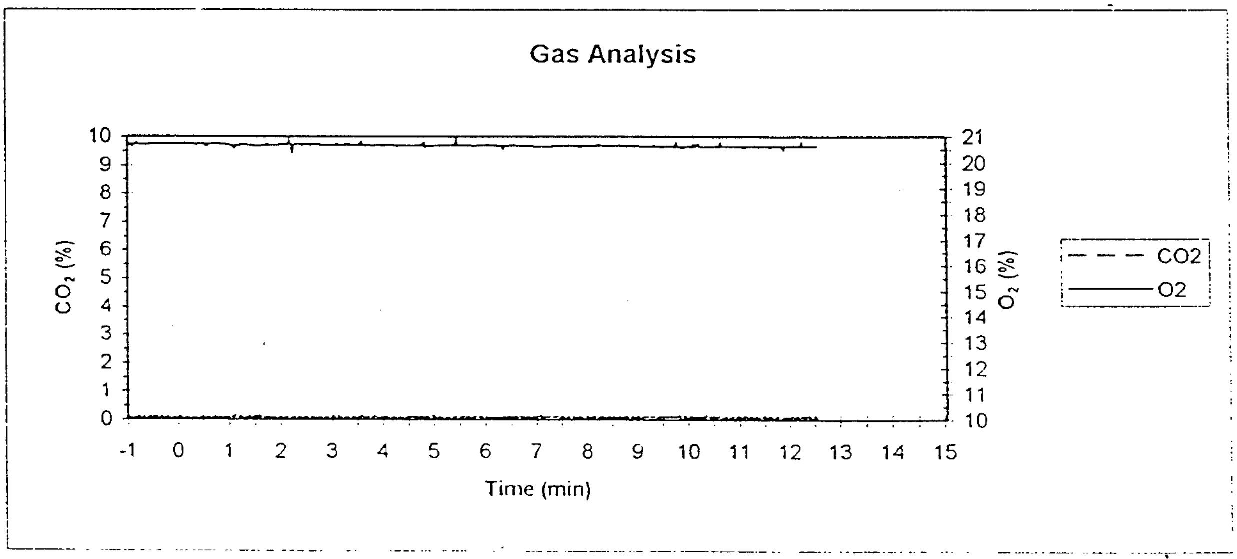
Nozzle Water Pressure
Pressure (MPa)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
600
500
400
300
200
100
0
-1
1
3
5
7
9
11
13
15
Time (min)

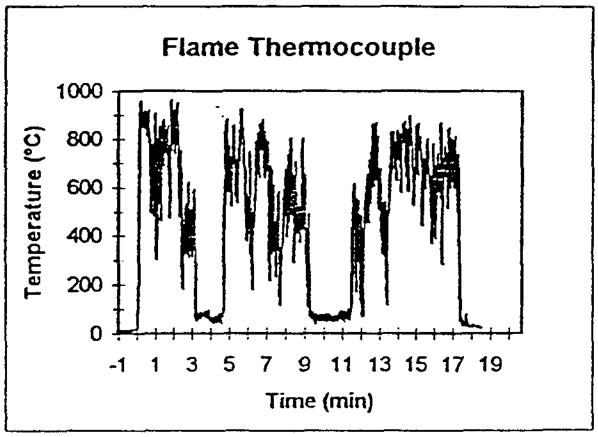


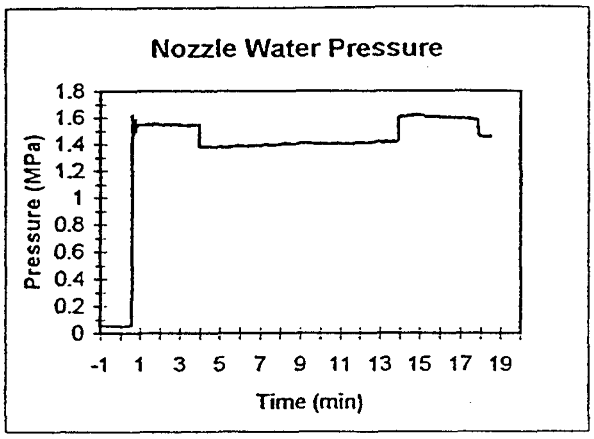
5 m Thermocouple (NW Corner)
Temperature (°C)
35
30
25
20
15
10
5
0
-1
1
3
5
7
9
11
13
15
Time (min)

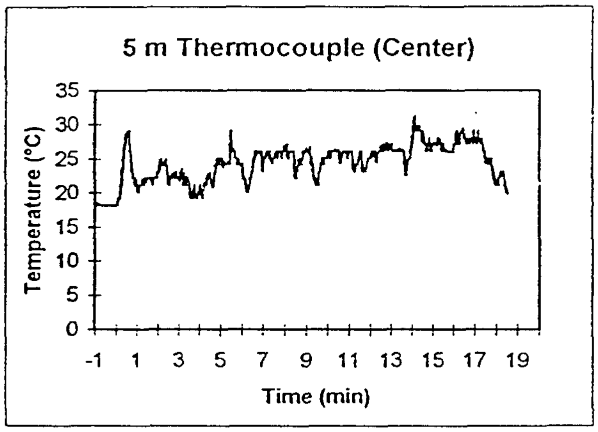


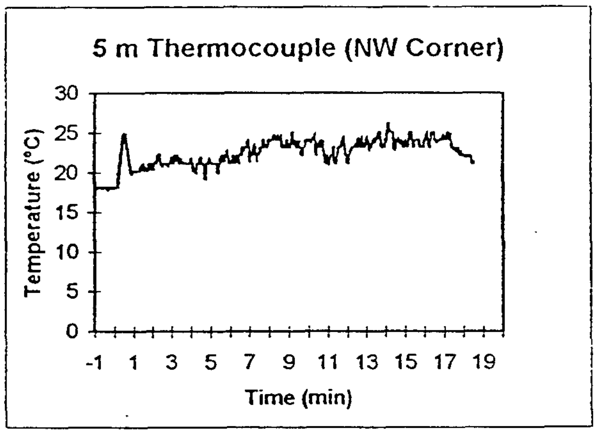
Gas Analysis
CO₂ (%)
O₂ (%)
10
9
8
7
6
5
4
3
2
1
0
21
20
19
18
17
16
15
14
13
12
11
10
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)
CO2
O2

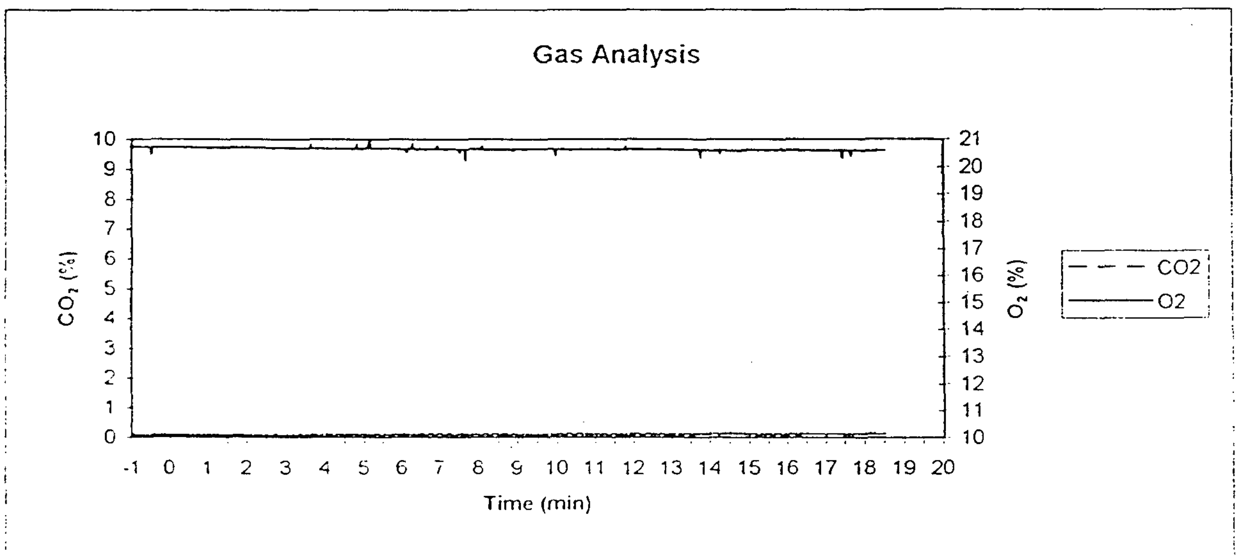
Test 6


Flame Thermocouple
Temperature (°C)
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)

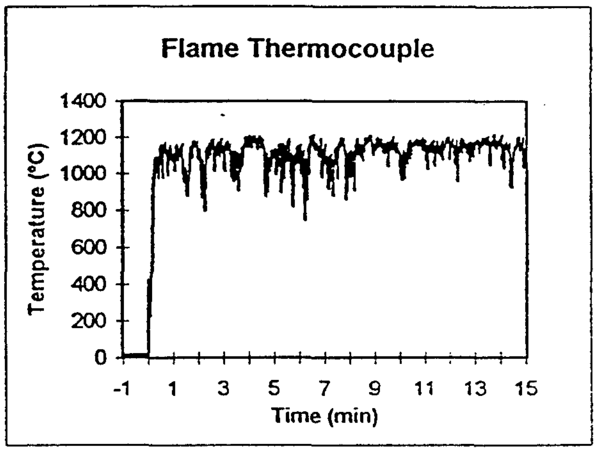

Nozzle Water Pressure
Pressure (MPa)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)


5 m Thermocouple (Center)
Temperature (°C)
35
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)

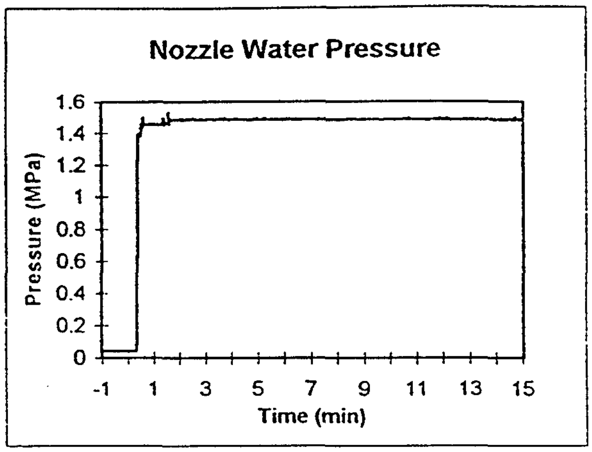

5 m Thermocouple (NW Corner)
Temperature (°C)
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)


Gas Analysis
CO2 (%)
10 9 8 7 6 5 4 3 2 1 0
O2 (%)
21 20 19 18 17 16 15 14 13 12 11 10
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time (min)

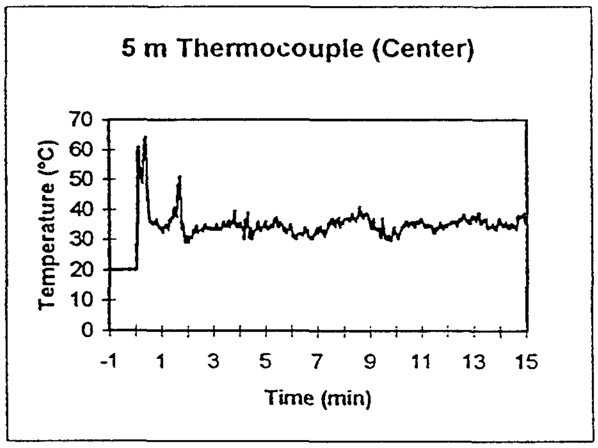
Test 7



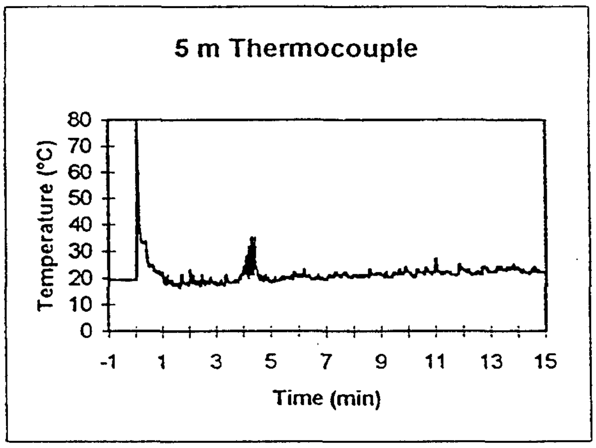
Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15
Time (min)



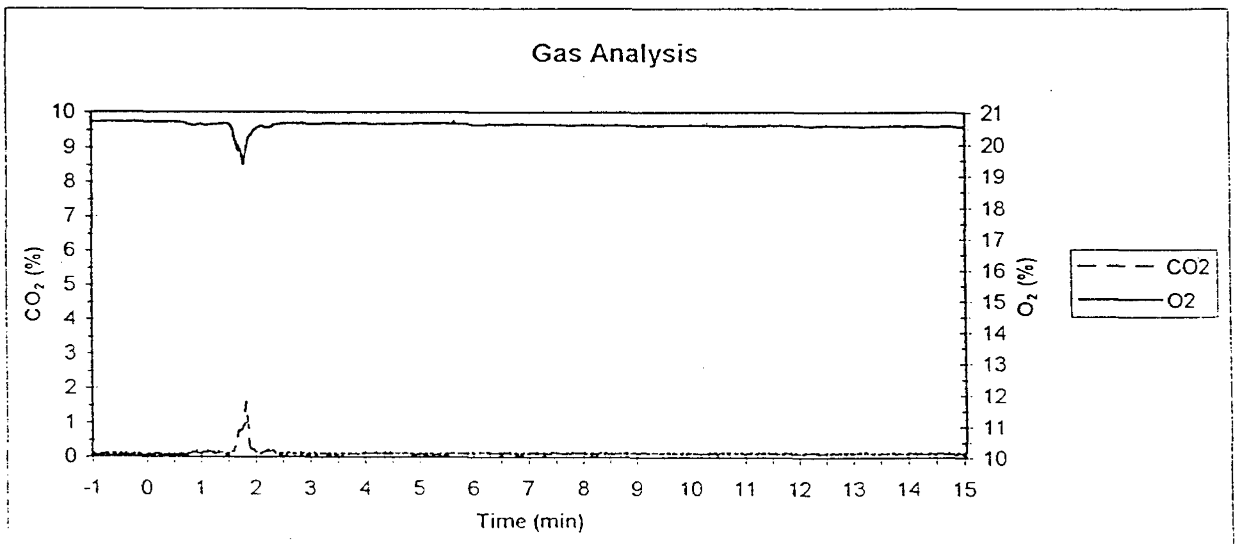
Nozzle Water Pressure
Pressure (MPa)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1 1 3 5 7 9 11 13 15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
70
60
50
40
30
20
10
0
-1 1 3 5 7 9 11 13 15
Time (min)

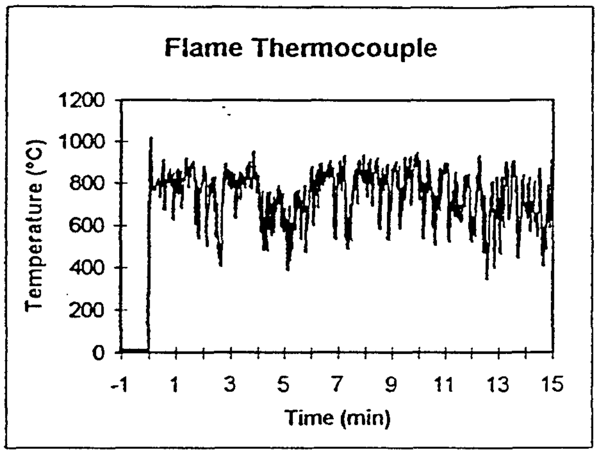


5 m Thermocouple
Temperature (°C)
80
70
60
50
40
30
20
10
0
-1 1 3 5 7 9 11 13 15
Time (min)

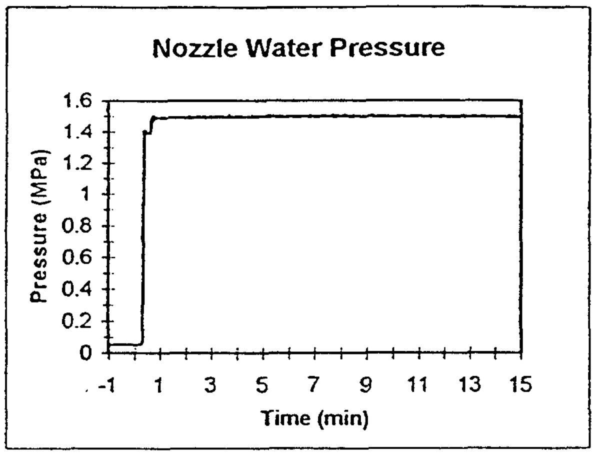


Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
21
20
19
18
17
16
15
14
13
12
11
10
O2 (%)
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (min)

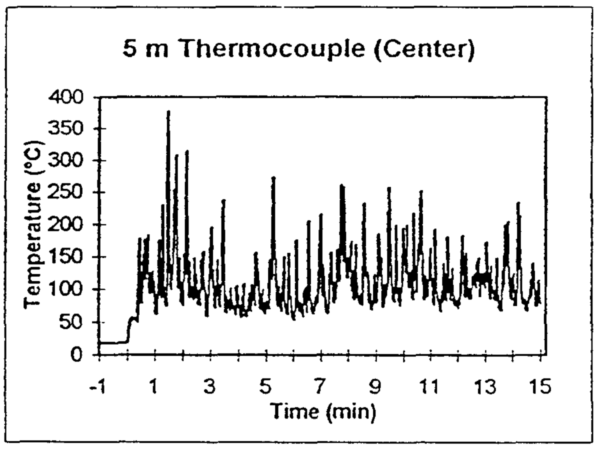
Test 8



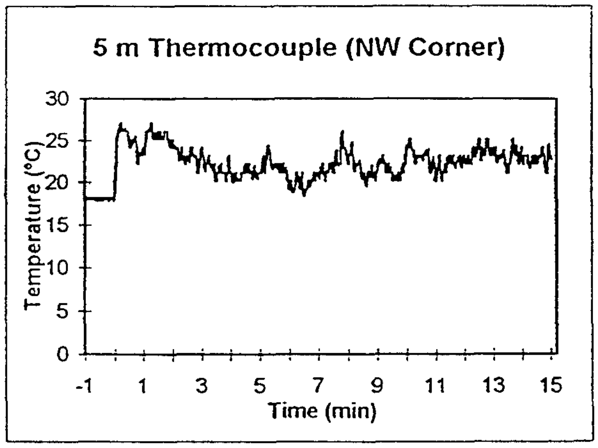
Flame Thermocouple
Temperature (°C)
0 200 400 600 800 1000 1200
-1 1 3 5 7 9 11 13 15
Time (min)



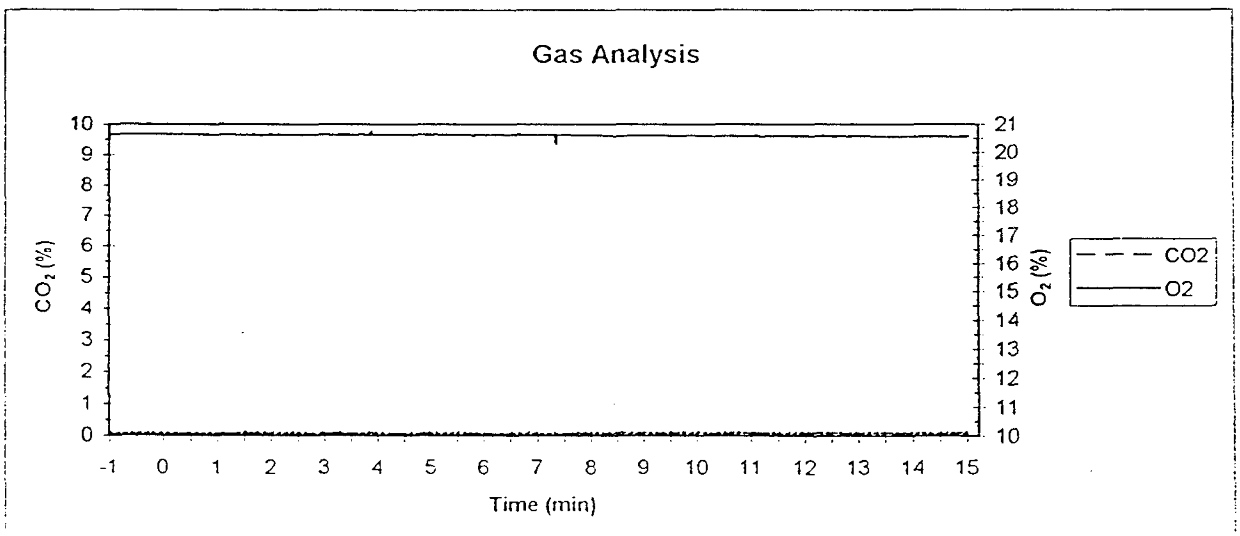
Nozzle Water Pressure
Pressure (MPa)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
-1 1 3 5 7 9 11 13 15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
0 50 100 150 200 250 300 350 400
-1 1 3 5 7 9 11 13 15
Time (min)

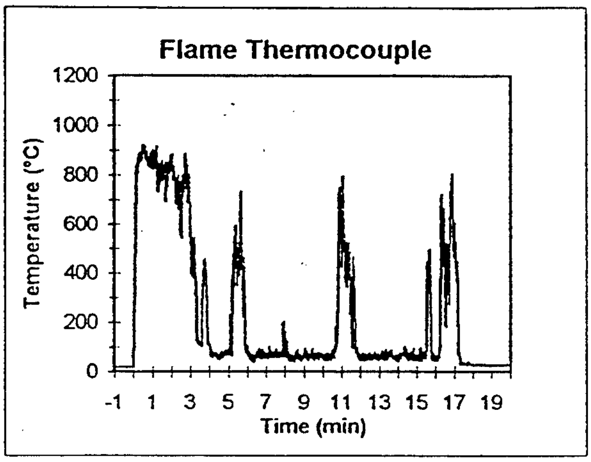


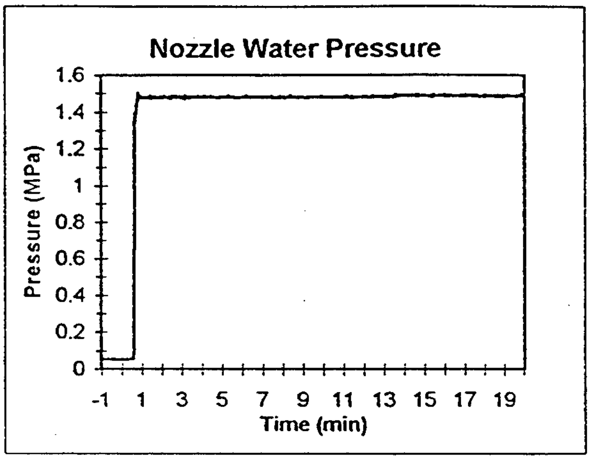
5 m Thermocouple (NW Corner)
Temperature (°C)
0 5 10 15 20 25 30
-1 1 3 5 7 9 11 13 15
Time (min)

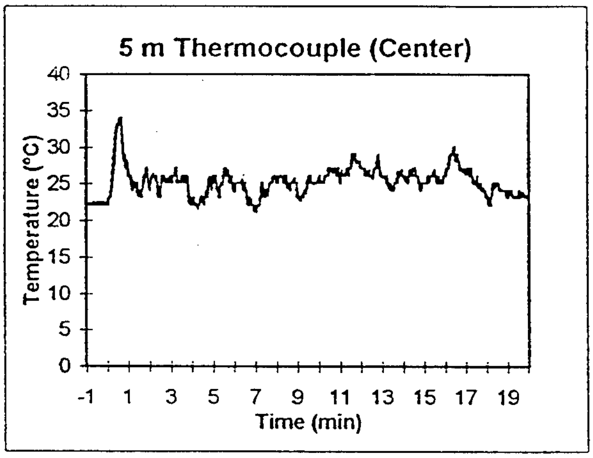


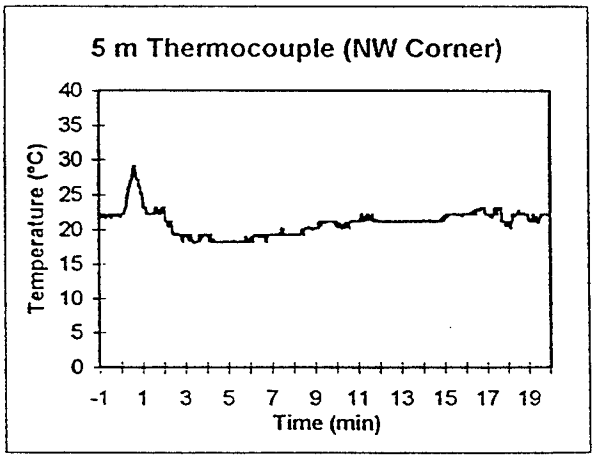
Gas Analysis
CO_2 (%)
0 1 2 3 4 5 6 7 8 9 10
O_2 (%)
10 11 12 13 14 15 16 17 18 19 20 21
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (min)

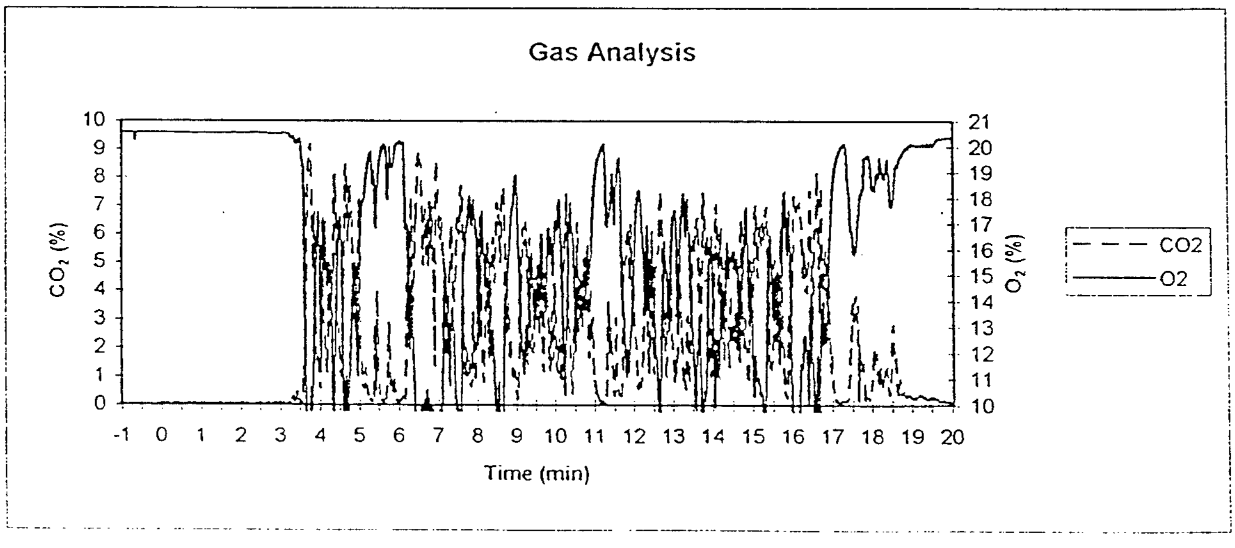
Test 9


Flame Thermocouple
Temperature (°C)
Time (min)
1200
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15 17 19

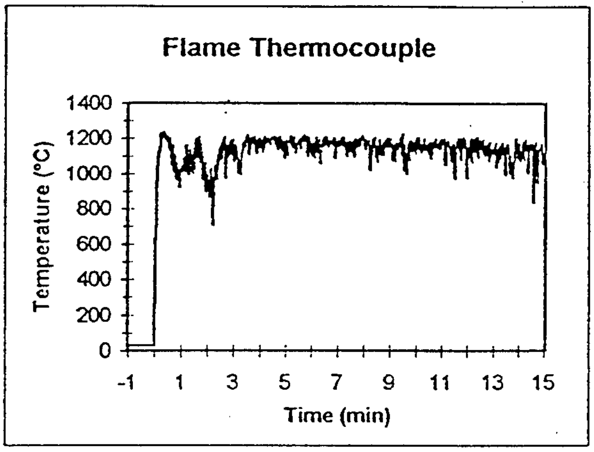

Nozzle Water Pressure
Pressure (MPa)
Time (min)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1 1 3 5 7 9 11 13 15 17 19


5 m Thermocouple (Center)
Temperature (°C)
Time (min)
40
35
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19

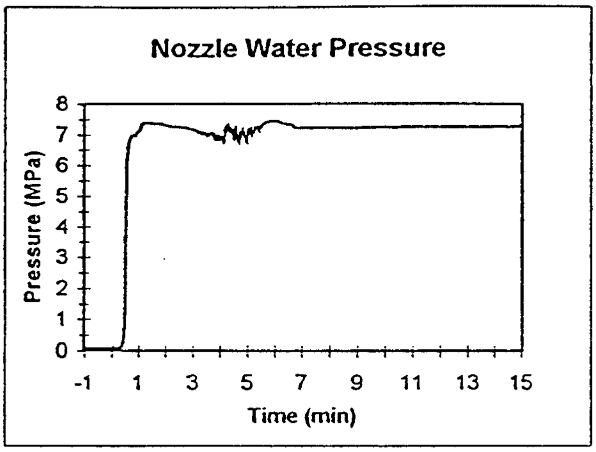

5 m Thermocouple (NW Corner)
Temperature (°C)
Time (min)
40
35
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19


Gas Analysis
CO2 (%)
O2 (%)
Time (min)
10 9 8 7 6 5 4 3 2 1 0
21 20 19 18 17 16 15 14 13 12 11 10
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
CO2
O2

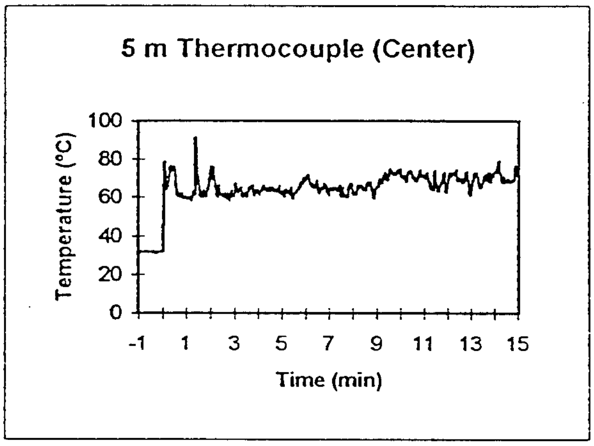
Test 10



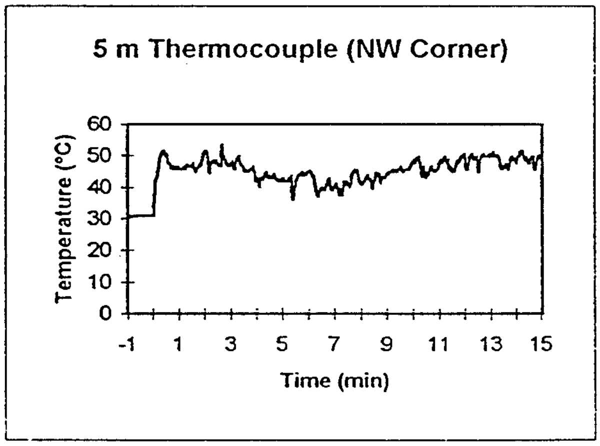
Flame Thermocouple
Temperature (°C)
0
200
400
600
800
1000
1200
1400
-1
1
3
5
7
9
11
13
15
Time (min)



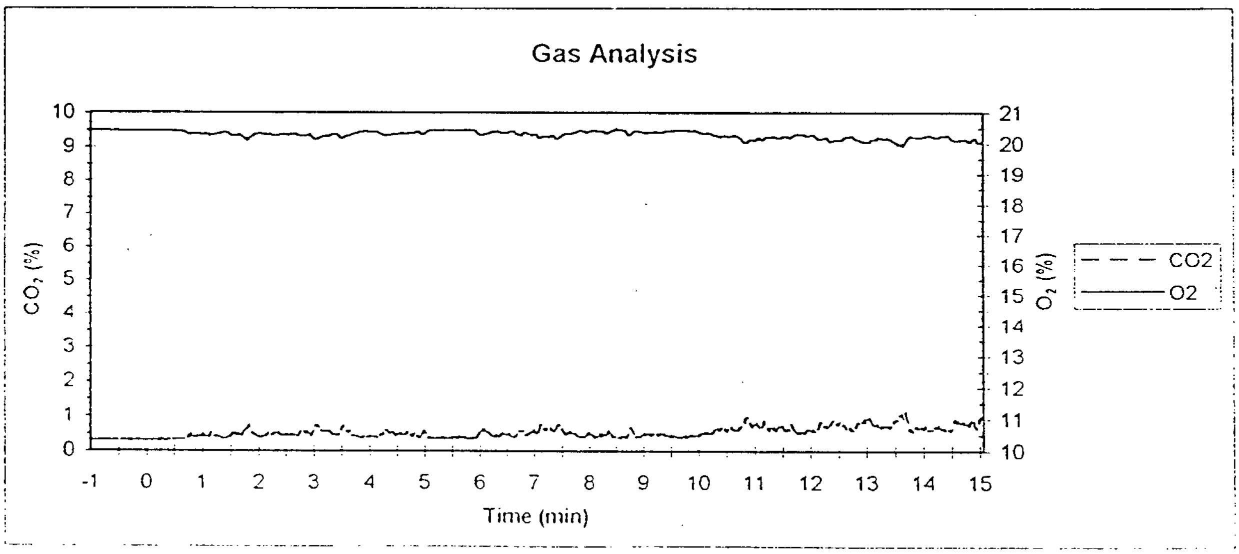
Nozzle Water Pressure
Pressure (MPa)
0
1
2
3
4
5
6
7
8
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
0
20
40
60
80
100
-1
1
3
5
7
9
11
13
15
Time (min)

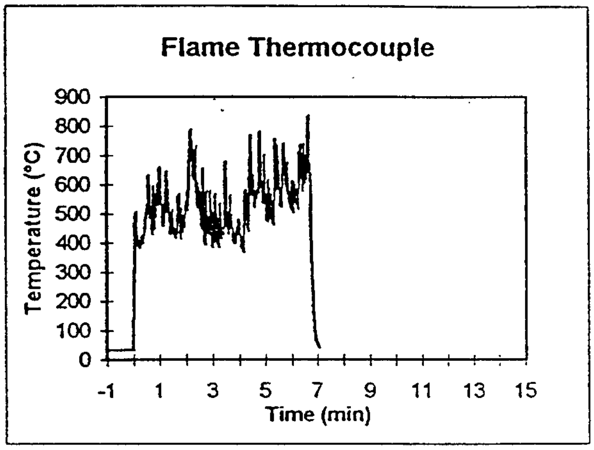


5 m Thermocouple (NW Corner)
Temperature (°C)
0
10
20
30
40
50
60
-1
1
3
5
7
9
11
13
15
Time (min)

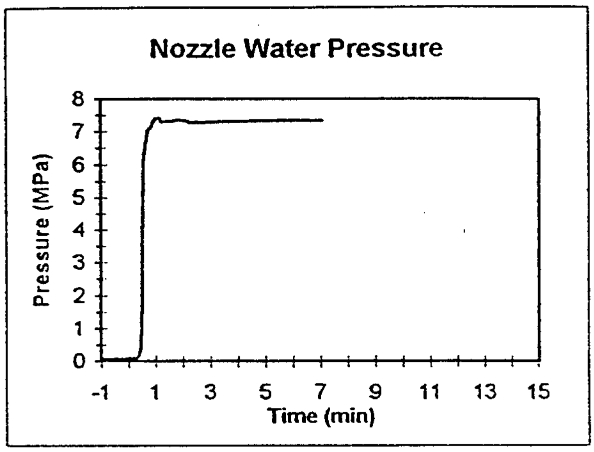


Gas Analysis
CO2 (%)
0
1
2
3
4
5
6
7
8
9
10
O2 (%)
10
11
12
13
14
15
16
17
18
19
20
21
CO2
O2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)

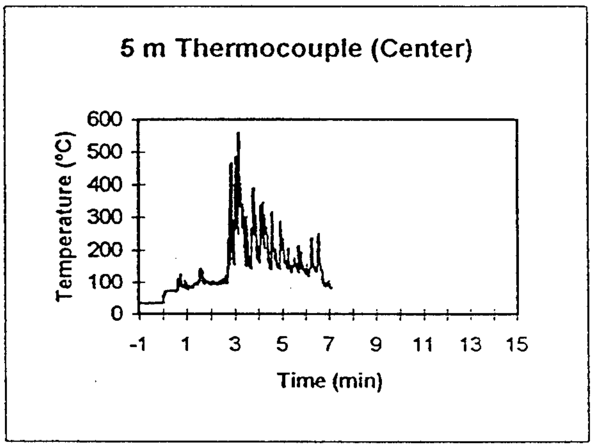
Test 11



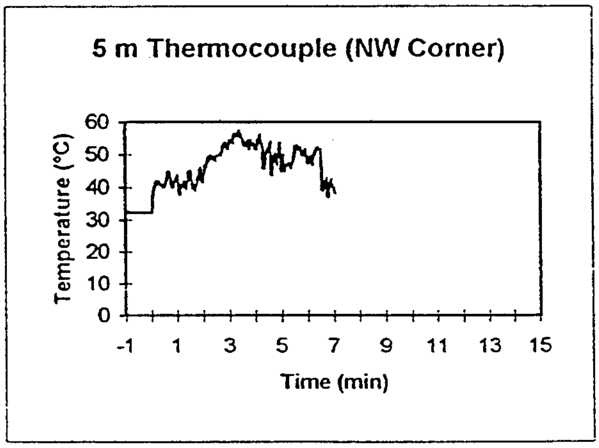
Flame Thermocouple
Temperature (°C)
Time (min)



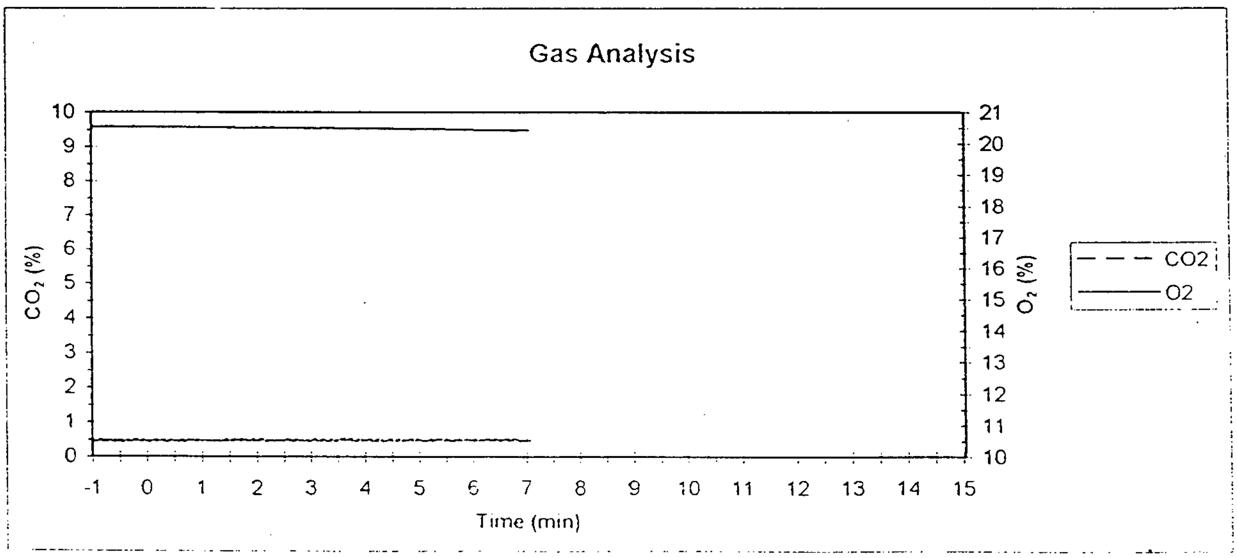
Nozzle Water Pressure
Pressure (MPa)
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
Time (min)

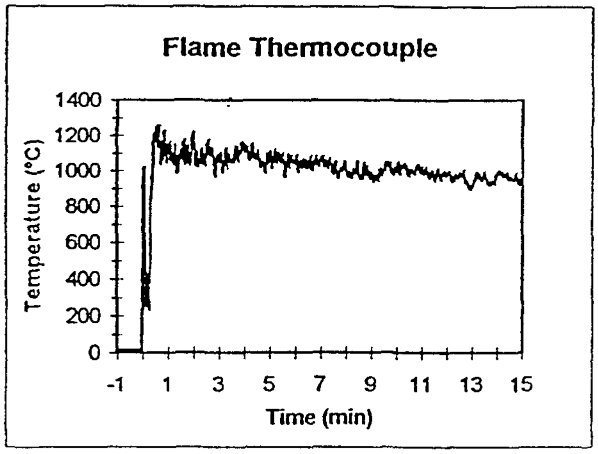


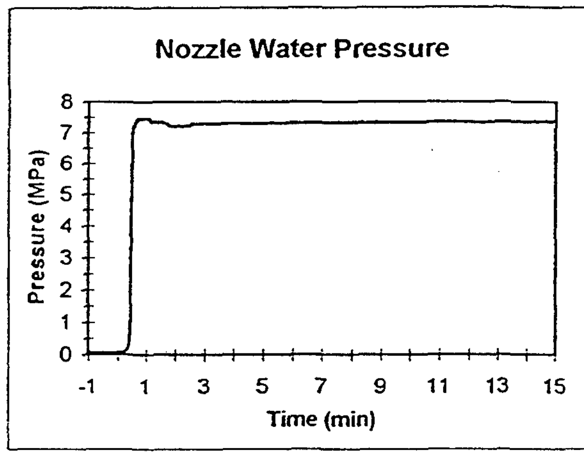
5 m Thermocouple (NW Corner)
Temperature (°C)
Time (min)

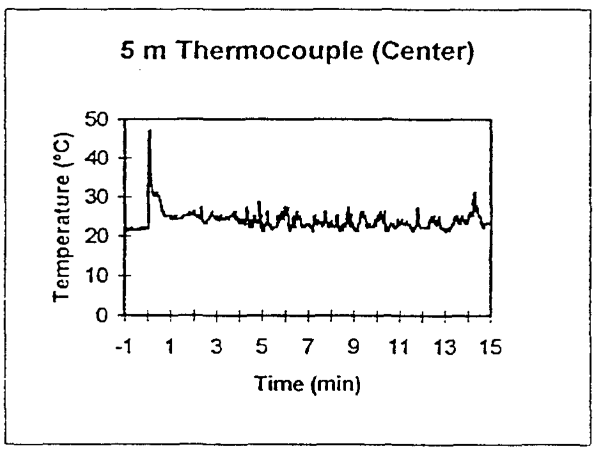


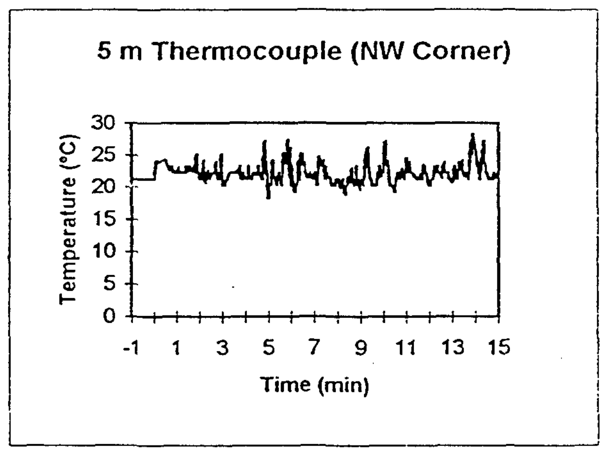
Gas Analysis
CO2 (%)
O2 (%)
CO2
O2
Time (min)

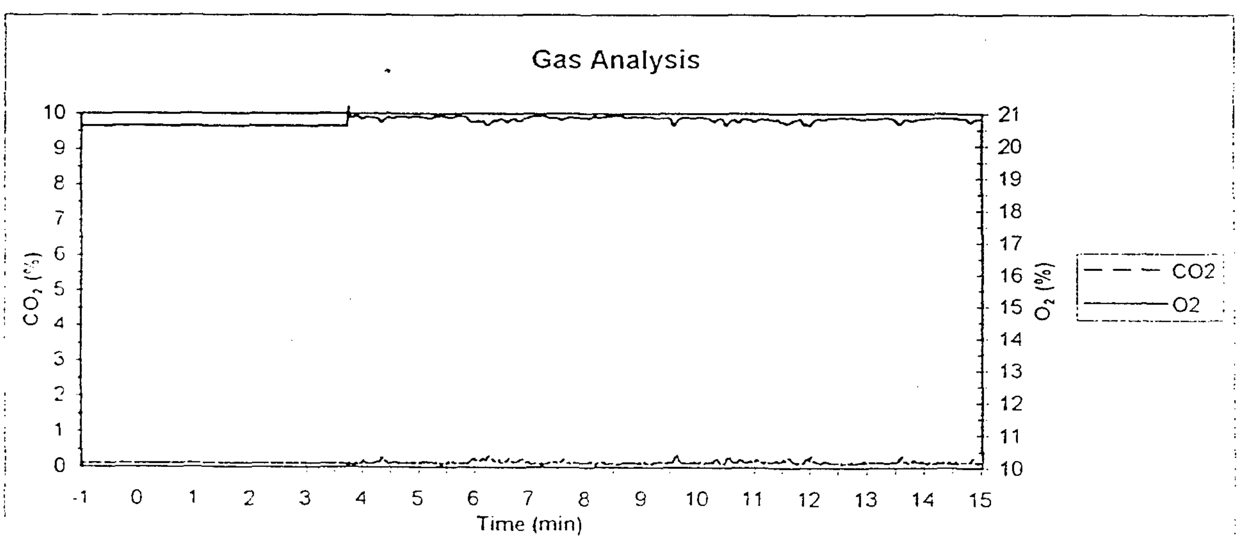
Test 12


Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15
Time (min)

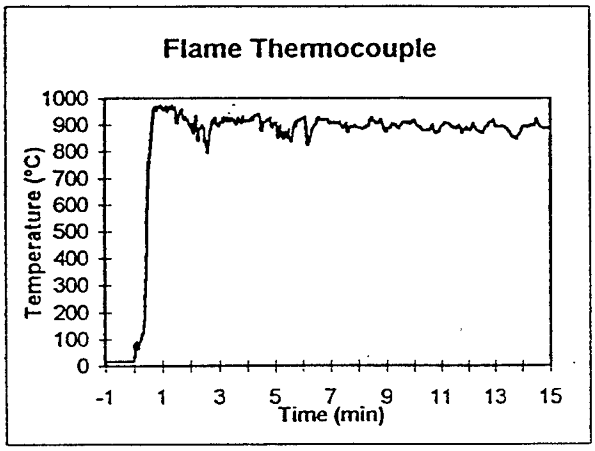

Nozzle Water Pressure
Pressure (MPa)
8
7
6
5
4
3
2
1
0
-1 1 3 5 7 9 11 13 15
Time (min)


5 m Thermocouple (Center)
Temperature (°C)
50
40
30
20
10
0
-1 1 3 5 7 9 11 13 15
Time (min)

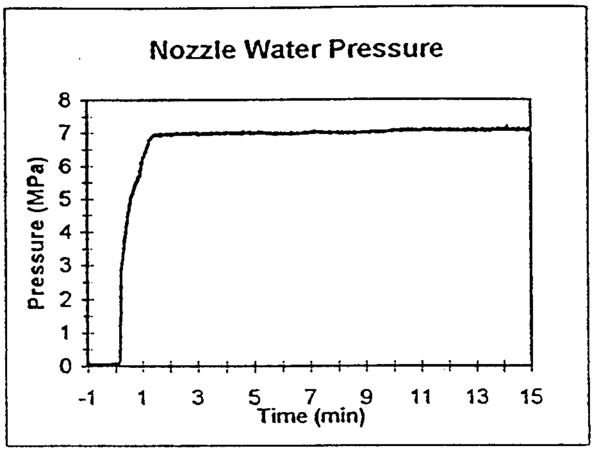

5 m Thermocouple (NW Corner)
Temperature (°C)
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15
Time (min)


Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
O2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (min)

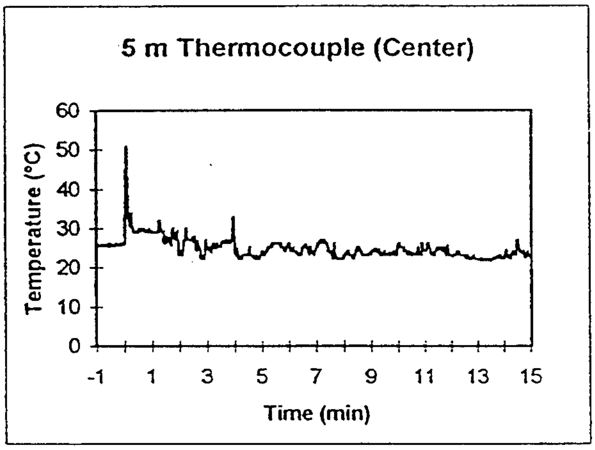
Test 13



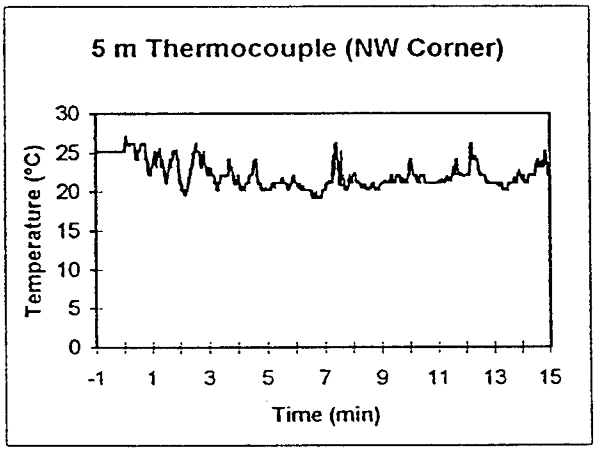
Flame Thermocouple
Temperature (°C)
1000
900
800
700
600
500
400
300
200
100
0
-1
1
3
5
7
9
11
13
15
Time (min)



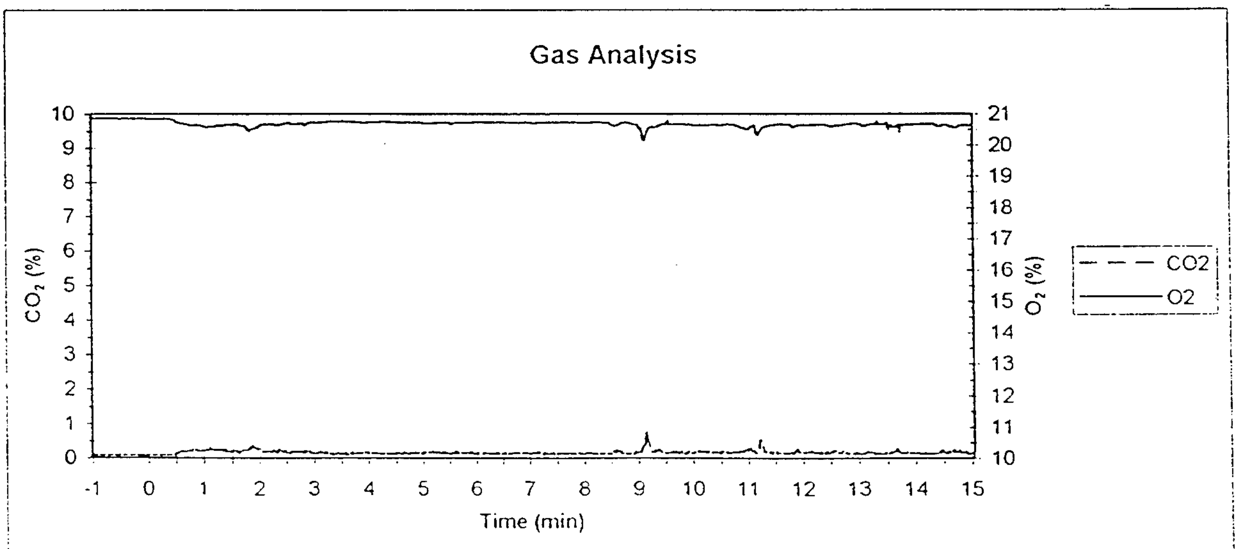
Nozzle Water Pressure
Pressure (MPa)
8
7
6
5
4
3
2
1
0
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
60
50
40
30
20
10
0
-1
1
3
5
7
9
11
13
15
Time (min)

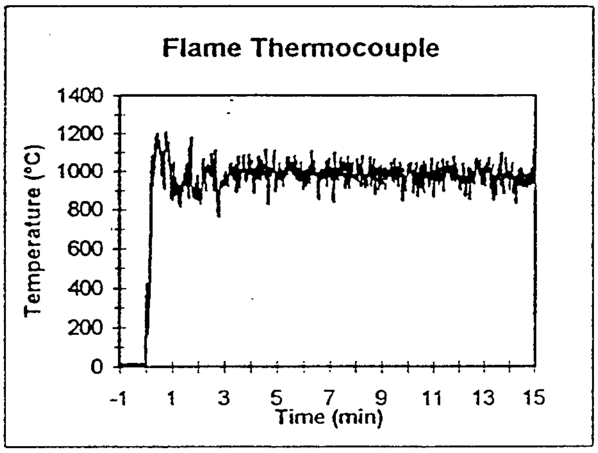


5 m Thermocouple (NW Corner)
Temperature (°C)
30
25
20
15
10
5
0
-1
1
3
5
7
9
11
13
15
Time (min)

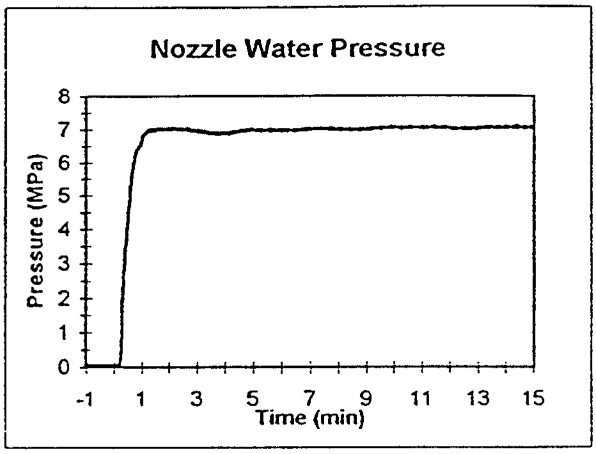


Gas Analysis
CO_2 (%)
10
9
8
7
6
5
4
3
2
1
0
O_2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
CO2
O2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)

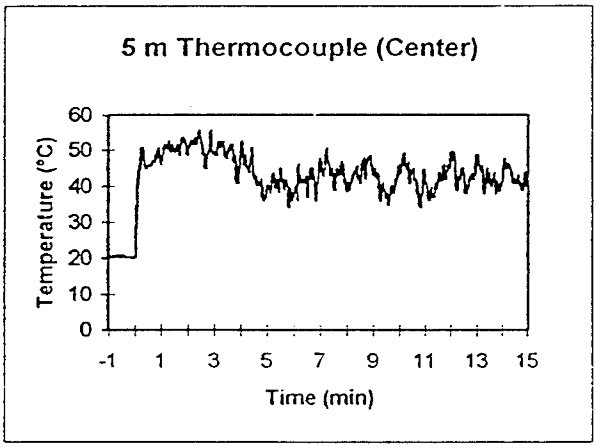
Test 14



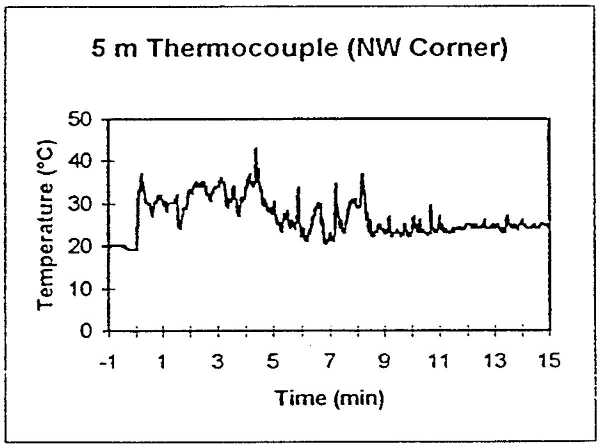
Flame Thermocouple
Temperature (°C)
1400
1200
1000
800
600
400
200
0
-1
1
3
5
7
9
11
13
15
Time (min)



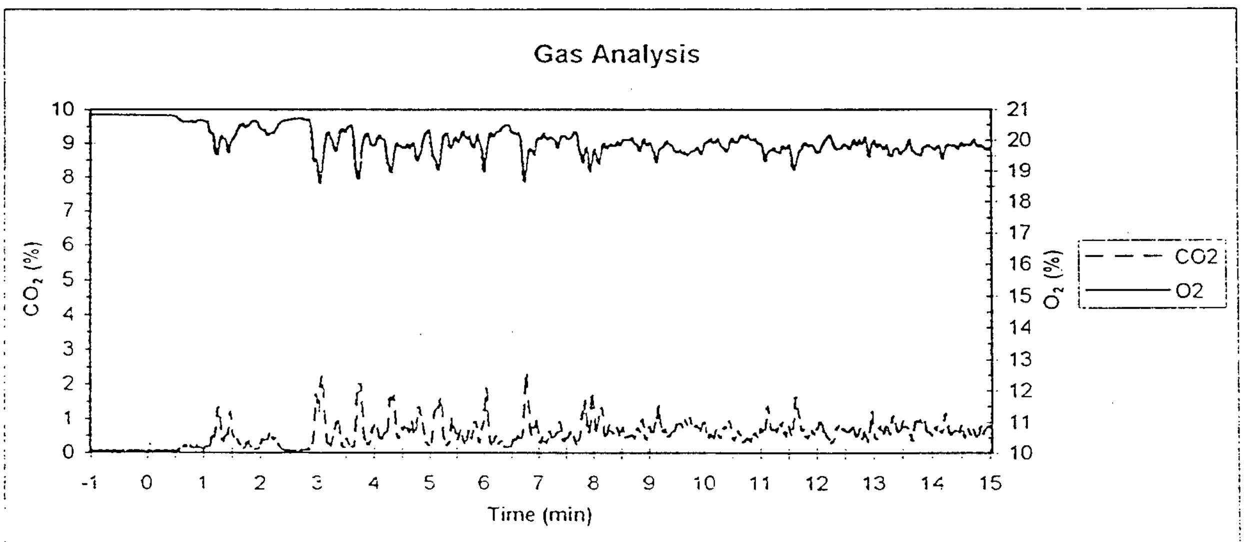
Nozzle Water Pressure
Pressure (MPa)
8
7
6
5
4
3
2
1
0
-1
1
3
5
7
9
11
13
15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
60
50
40
30
20
10
0
-1
1
3
5
7
9
11
13
15
Time (min)

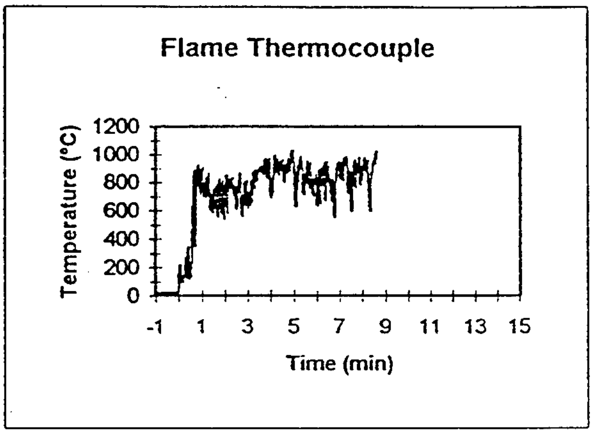


5 m Thermocouple (NW Corner)
Temperature (°C)
50
40
30
20
10
0
-1
1
3
5
7
9
11
13
15
Time (min)

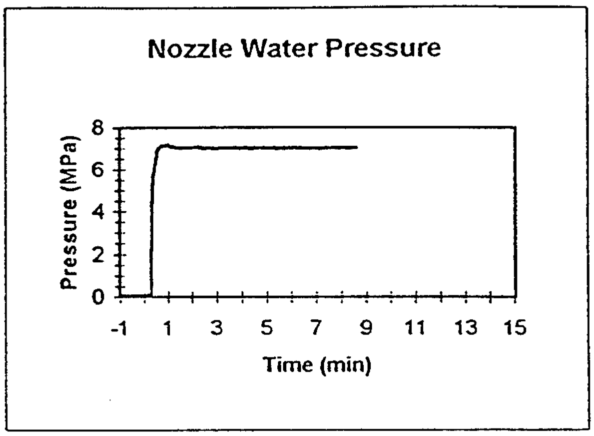


Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
O2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
CO2
O2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time (min)

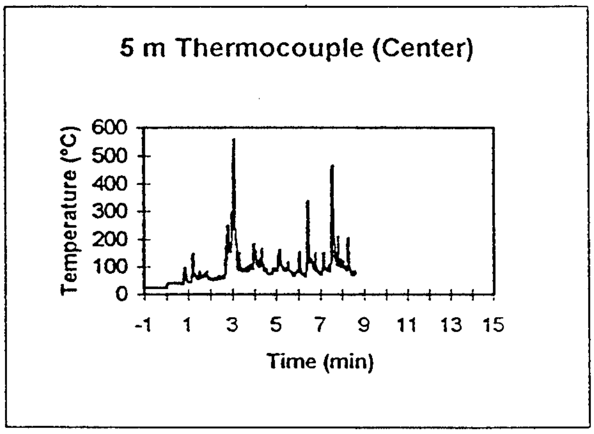
Test 15



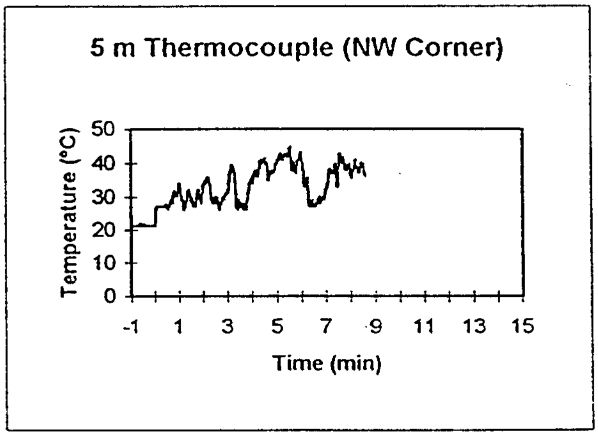
Flame Thermocouple
Temperature (°C)
1200
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15
Time (min)



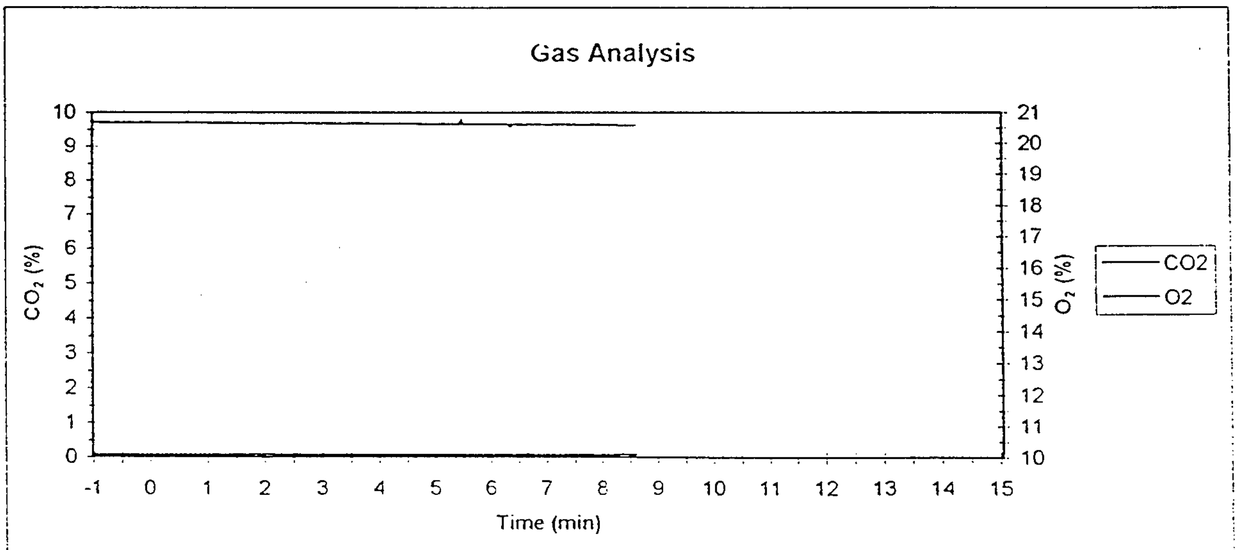
Nozzle Water Pressure
Pressure (MPa)
8
6
4
2
0
-1 1 3 5 7 9 11 13 15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
600
500
400
300
200
100
0
-1 1 3 5 7 9 11 13 15
Time (min)

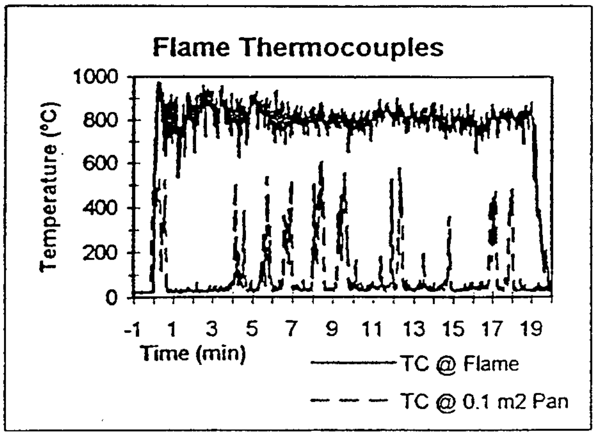


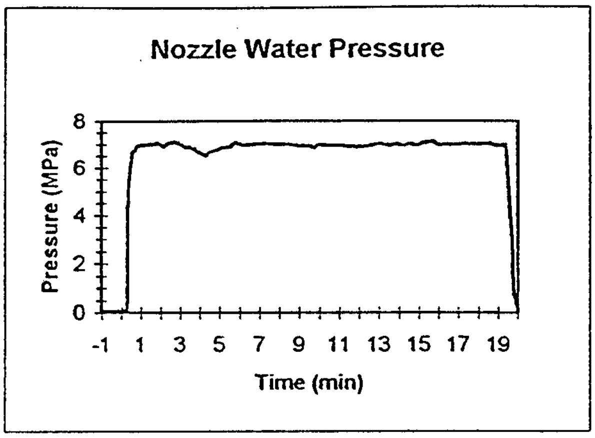
5 m Thermocouple (NW Corner)
Temperature (°C)
50
40
30
20
10
0
-1 1 3 5 7 9 11 13 15
Time (min)

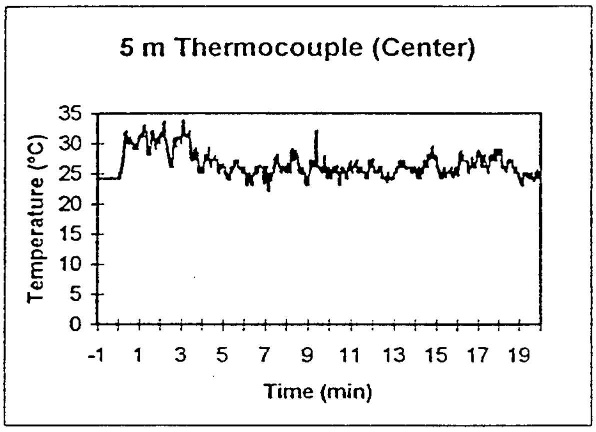


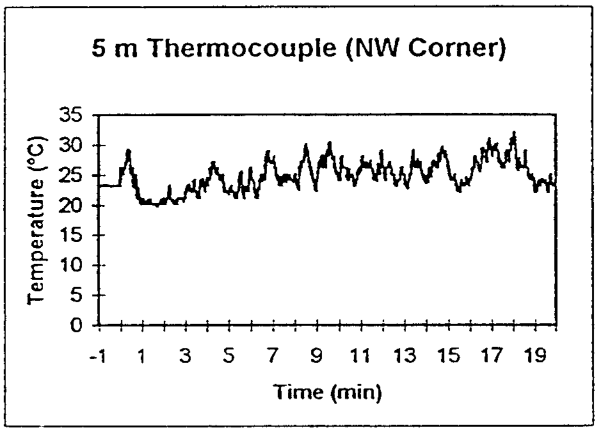
Gas Analysis
CO2 (%)
10 9 8 7 6 5 4 3 2 1 0
O2 (%)
21 20 19 18 17 16 15 14 13 12 11 10
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (min)
CO2
O2

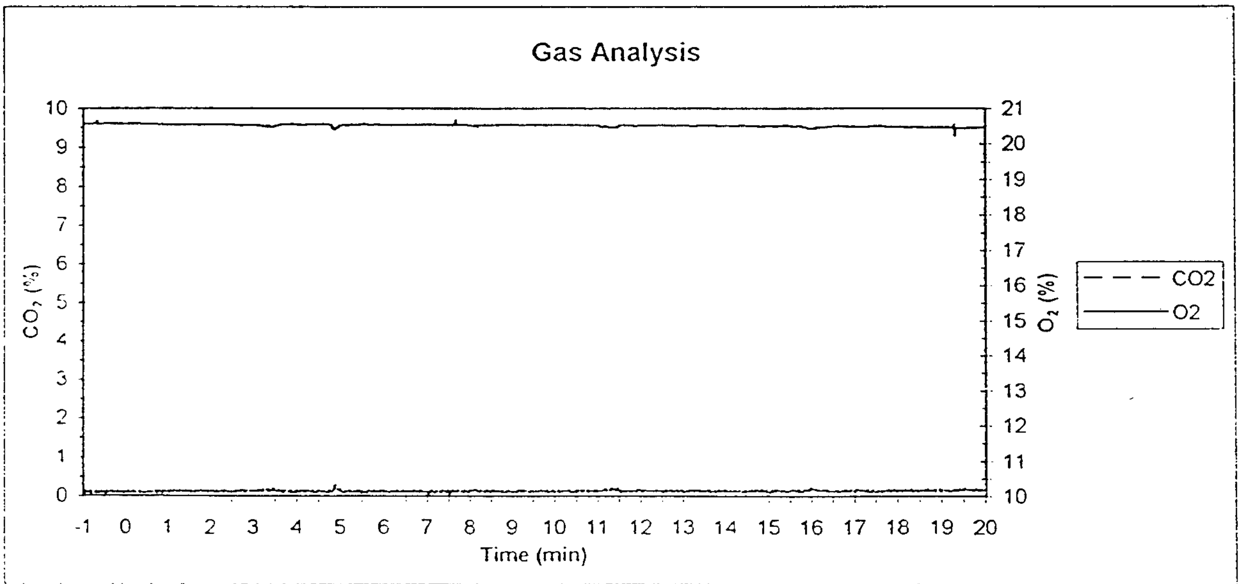
Test 16


Flame Thermocouples
Temperature (°C)
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)
TC @ Flame
TC @ 0.1 m2 Pan

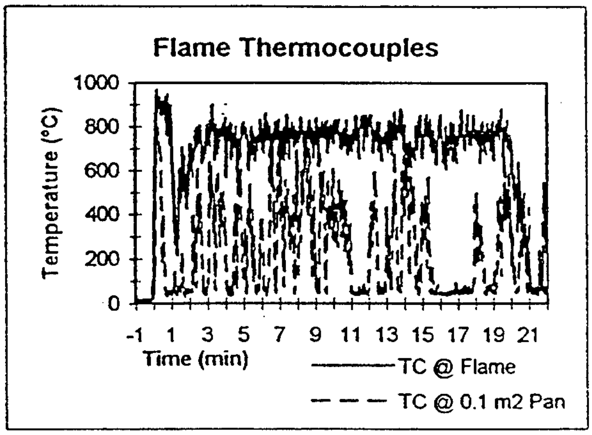

Nozzle Water Pressure
Pressure (MPa)
8
6
4
2
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)

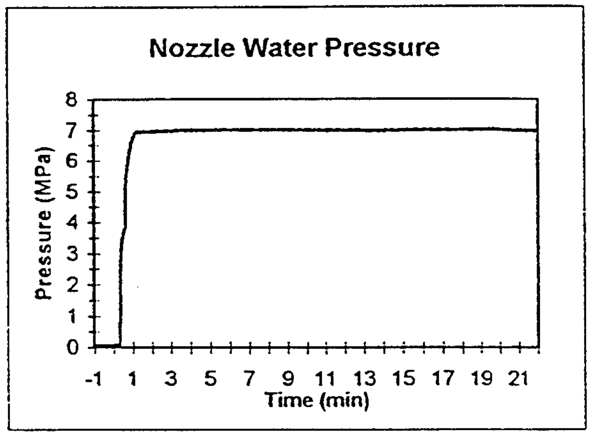

5 m Thermocouple (Center)
Temperature (°C)
35
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)

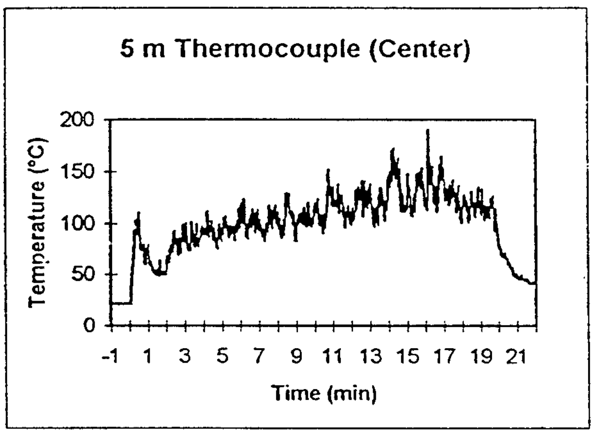

5 m Thermocouple (NW Corner)
Temperature (°C)
35
30
25
20
15
10
5
0
-1 1 3 5 7 9 11 13 15 17 19
Time (min)

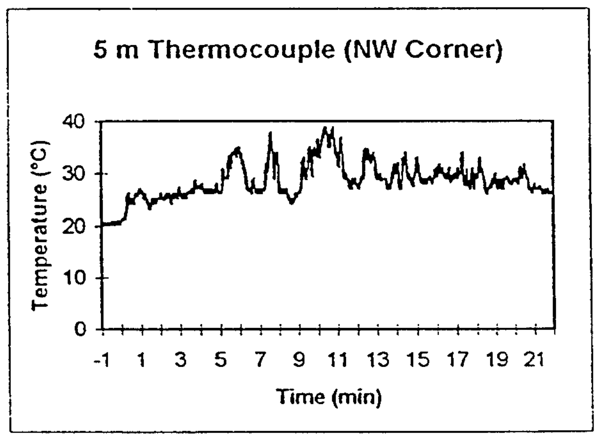

Gas Analysis
10 9 8 7 6 5 4 3 2 1 0
CO2 (%)
21 20 19 18 17 16 15 14 13 12 11 10
O2 (%)
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time (min)
CO2
O2

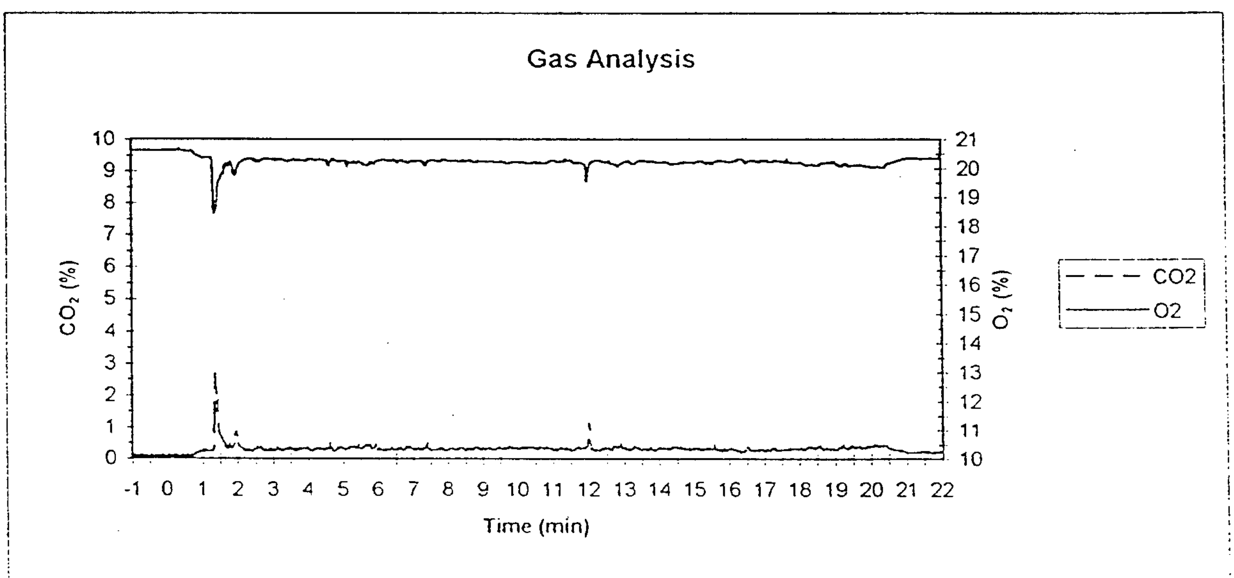
Test 17


Flame Thermocouples
Temperature (°C)
1000
800
600
400
200
0
-1 1 3 5 7 9 11 13 15 17 19 21
Time (min)
TC @ Flame
TC @ 0.1 m2 Pan

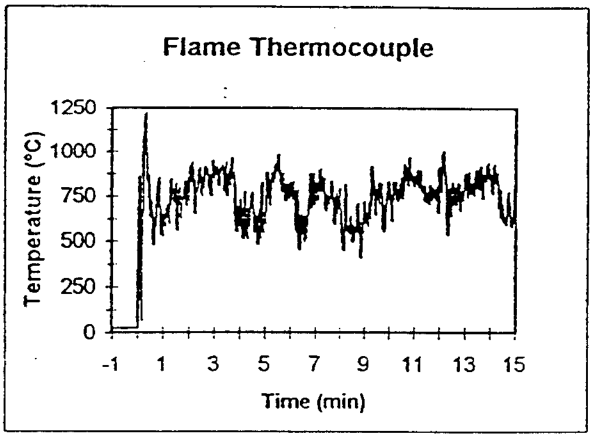

Nozzle Water Pressure
Pressure (MPa)
8
7
6
5
4
3
2
1
0
-1 1 3 5 7 9 11 13 15 17 19 21
Time (min)


5 m Thermocouple (Center)
Temperature (°C)
200
150
100
50
0
-1 1 3 5 7 9 11 13 15 17 19 21
Time (min)

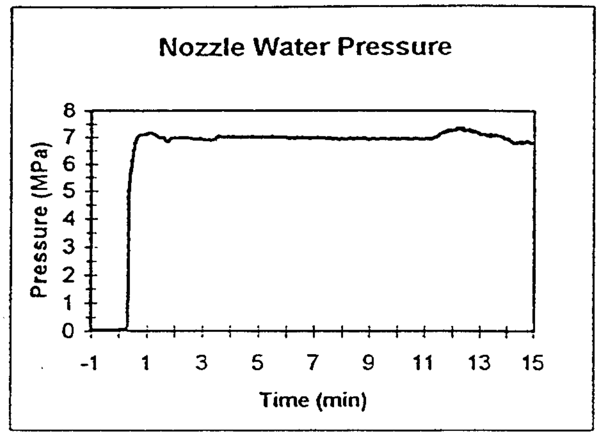

5 m Thermocouple (NW Corner)
Temperature (°C)
40
30
20
10
0
-1 1 3 5 7 9 11 13 15 17 19 21
Time (min)


Gas Analysis
CO2 (%)
10
9
8
7
6
5
4
3
2
1
0
O2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Time (min)
CO2
O2

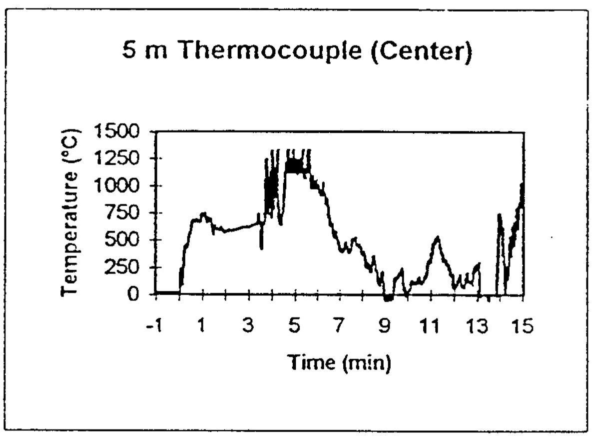
Test 18



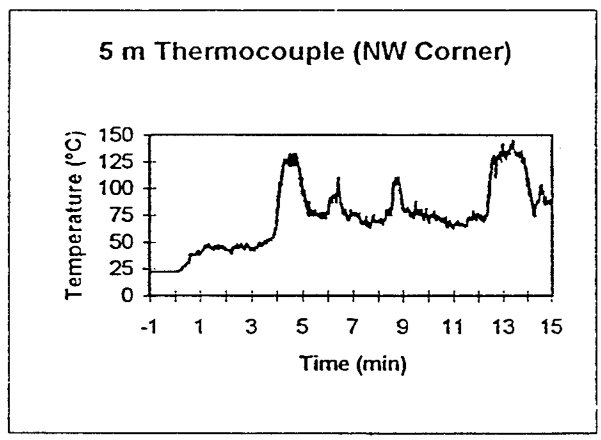
Flame Thermocouple
Temperature (°C)
1250
1000
750
500
250
0
-1 1 3 5 7 9 11 13 15
Time (min)



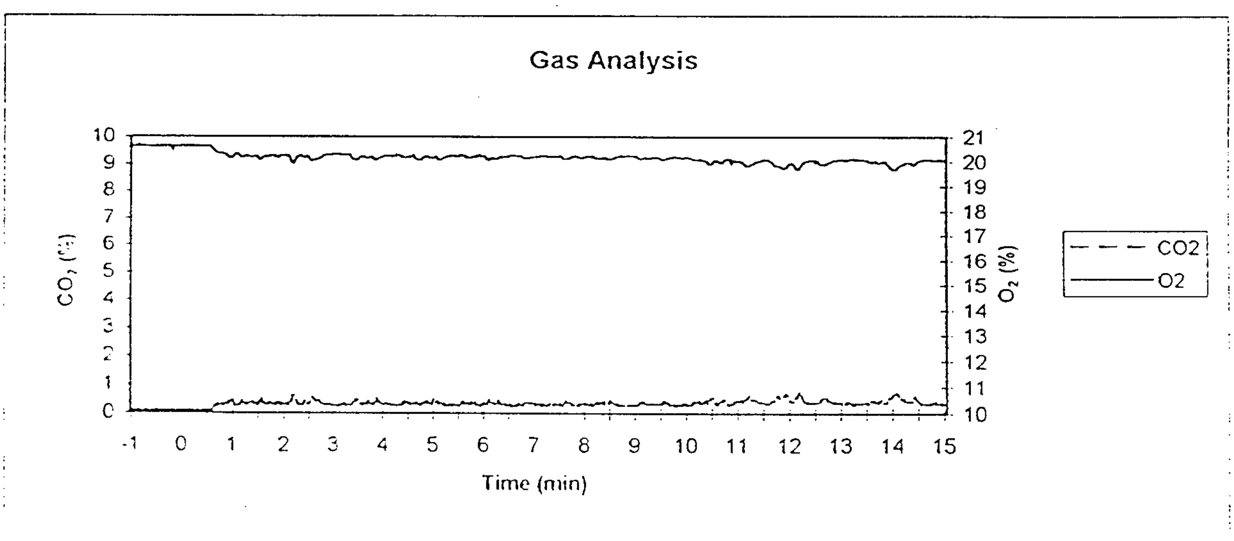
Nozzle Water Pressure
Pressure (MPa)
8
7
6
5
4
3
2
1
0
-1 1 3 5 7 9 11 13 15
Time (min)



5 m Thermocouple (Center)
Temperature (°C)
1500
1250
1000
750
500
250
0
-1 1 3 5 7 9 11 13 15
Time (min)

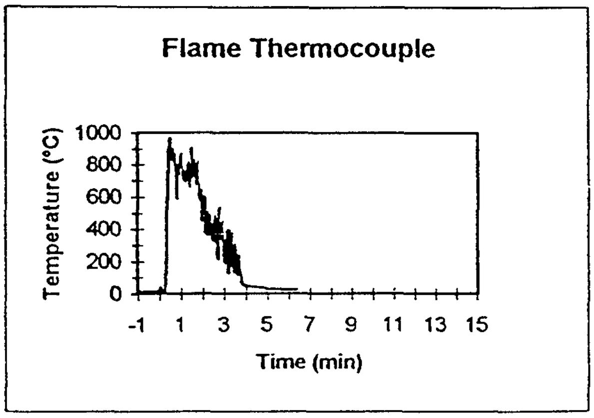


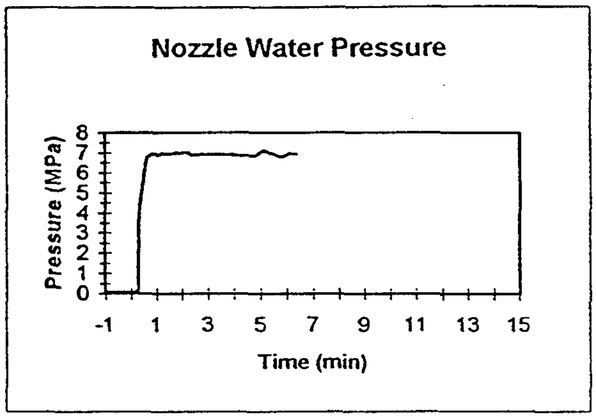
5 m Thermocouple (NW Corner)
Temperature (°C)
150
125
100
75
50
25
0
-1 1 3 5 7 9 11 13 15
Time (min)



Gas Analysis
CO_2 (%)
10
9
8
7
6
5
4
3
2
1
0
O_2 (%)
21
20
19
18
17
16
15
14
13
12
11
10
CO2
O2
-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Time (min)

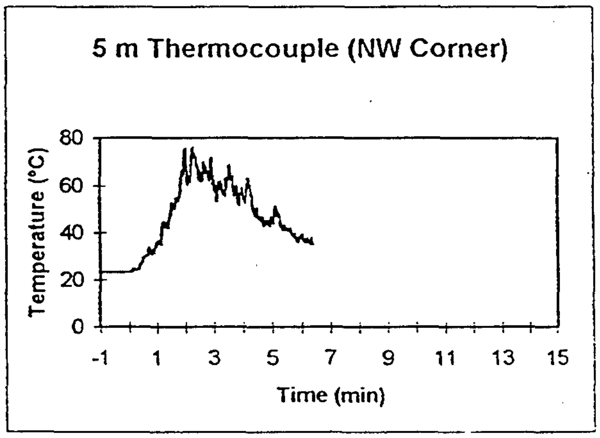
Test 19

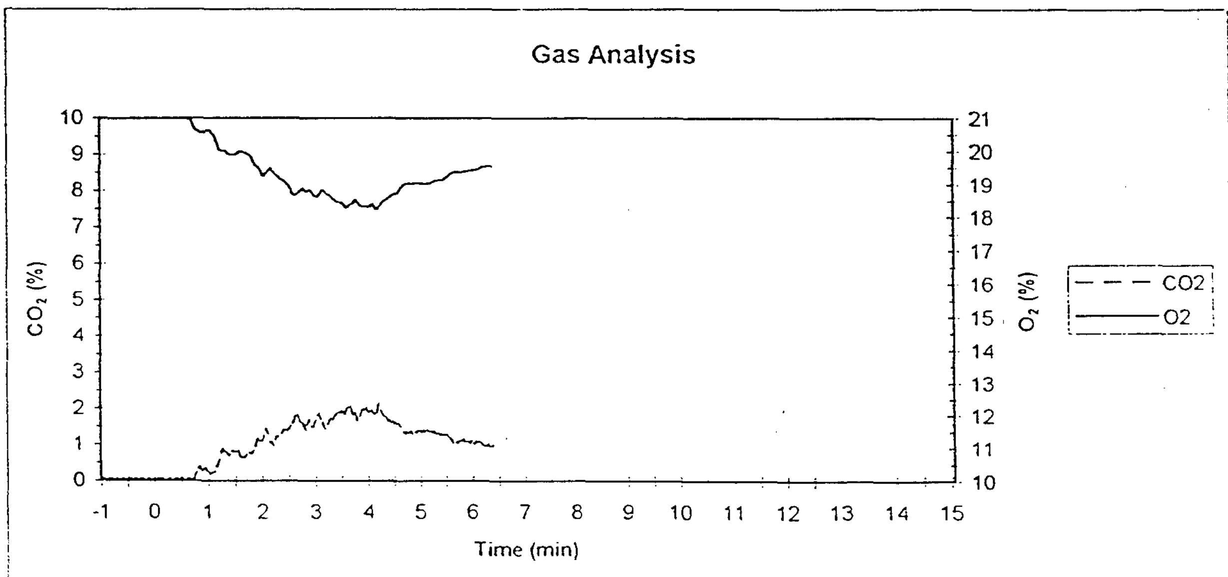




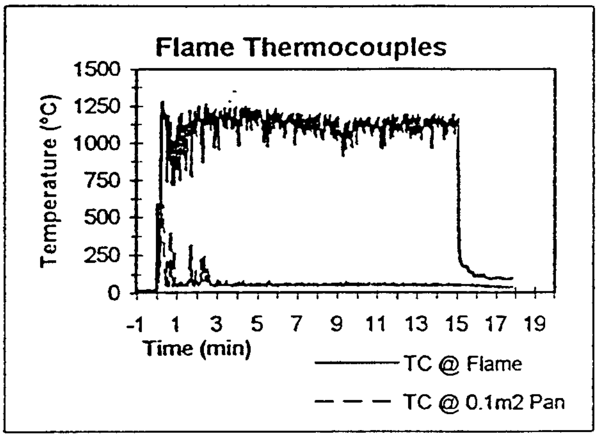
5 m Thermocouple (Center)

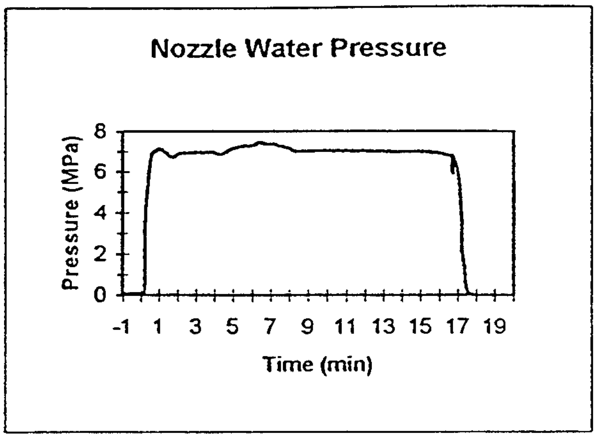
Malfunction





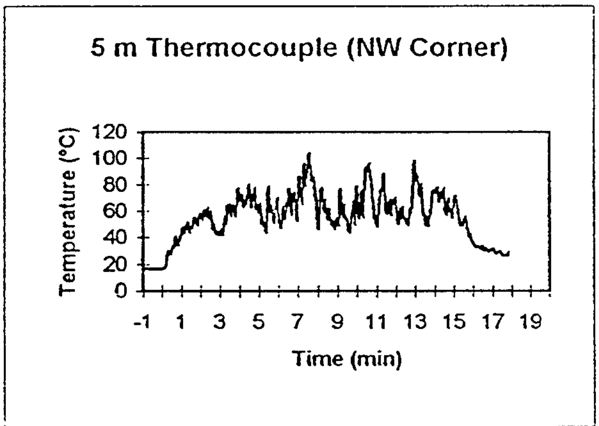
Test 20

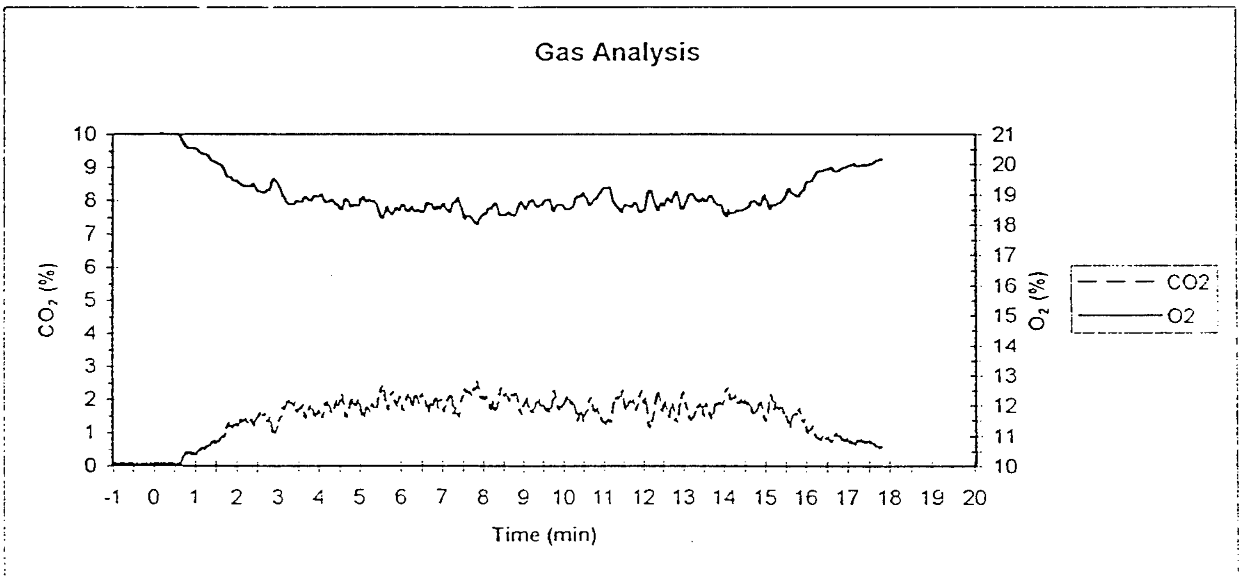




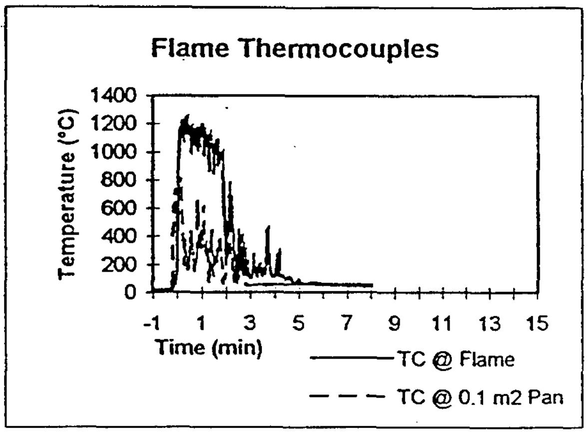
5 m Thermocouple
(Center)

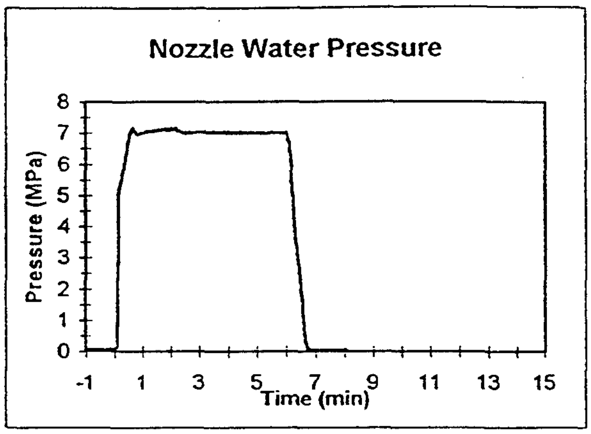
Malfunction





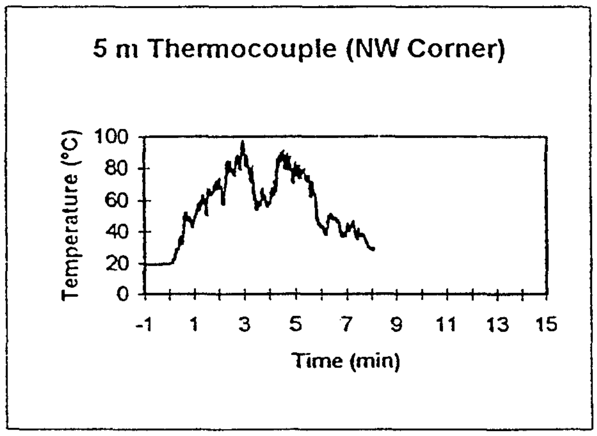
Test 21

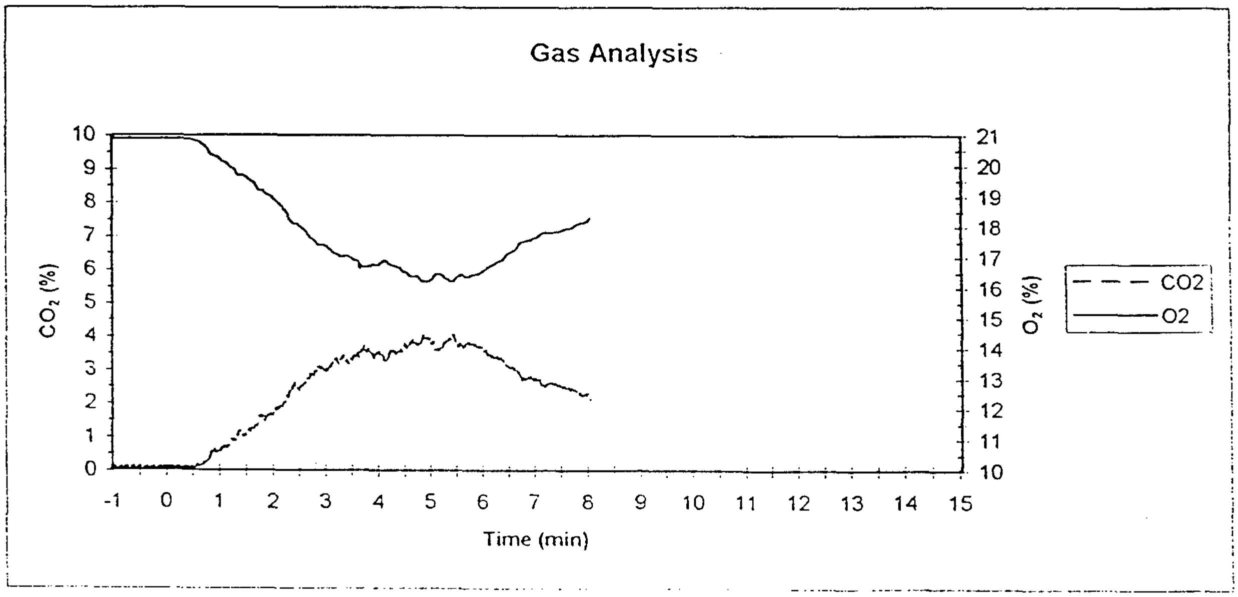




5 m Thermocouple (Center)

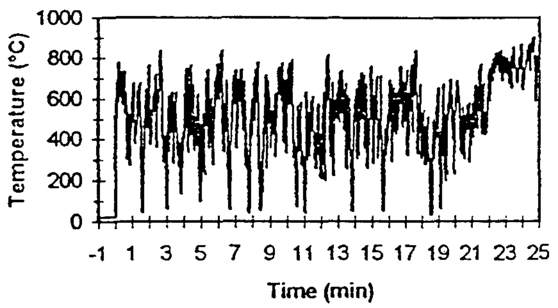
Malfunction



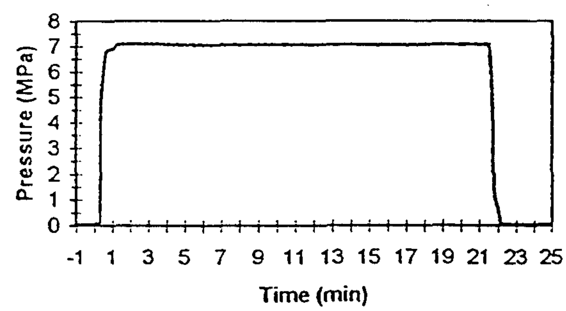


Test 22

Flame Thermocouple



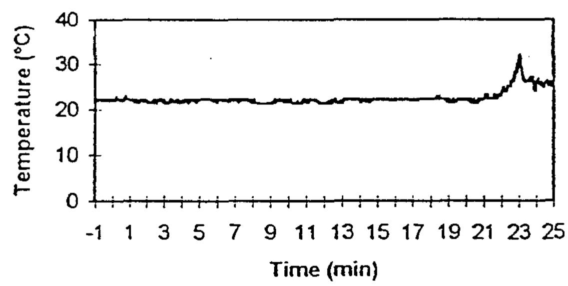
Nozzle Water Pressure



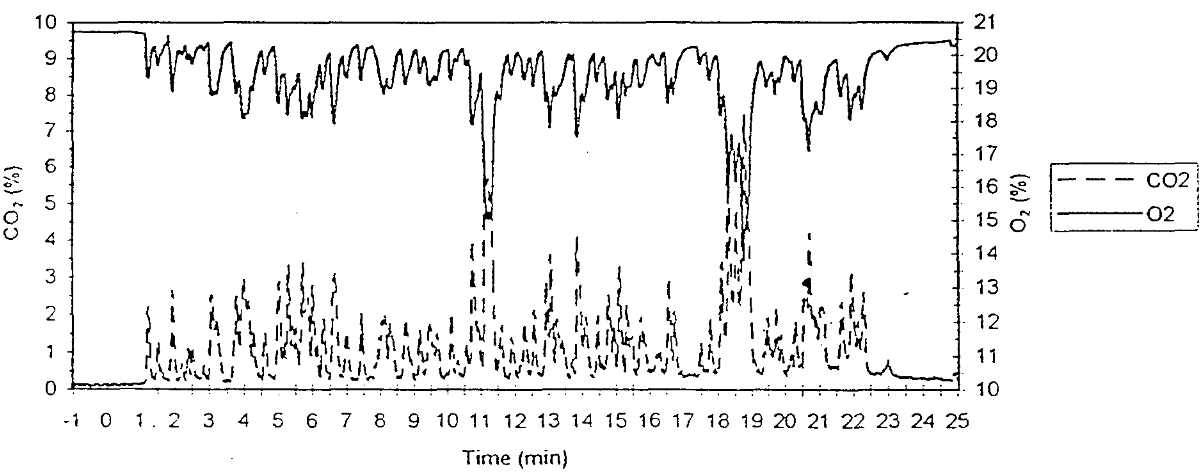
5 m Thermocouple (Center)

Malfunction

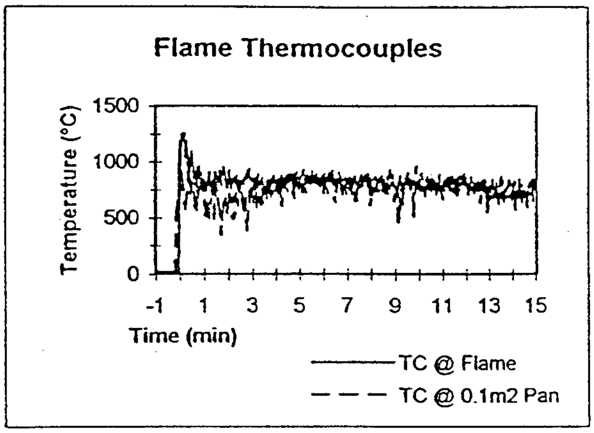
5 m Thermocouple (NW Corner)

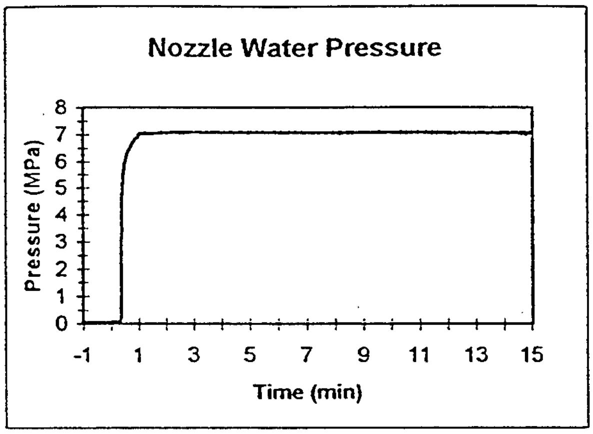


Gas Analysis



Test 23





5 m Thermocouple (Center)

Malfunction